Meeting on Asteroids and Comets in Europe MACE 2003



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Meeting on Asteroids and Comets in Europe MACE 2003



May, 1-4 Costitx - Mallorca SPAIN

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# **MACE 2003**

Meeting on Asteroids and Comets in Europe May, 1-4, 2003. Costitx, Mallorca, Spain

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# REFLECTANCE SPECTROSCOPY AND THE CHEMICAL AND PHYSICAL PROPERTIES OF ASTEROIDS

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Asteroids have become objects of intense interest for planetary astronomers. They occupy the transition zone between the dense, volatile-poor terrestrial planets and the icy, gas-rich outer planets and satellites. Although a thorough under-standing of the nature of asteroids is very important for science and because some of them may be potential impactors, we have not yet analysed directly any asteroid, either in situ or by sample return. Meteorites represent our best choice to know the physical and chemical characteristics of asteroids, but we do not know to what extent the information revealed by meteorites is representative enough. Therefore we need to obtain additional data using telescopes on Earth. Reflectance spectroscopy in the wave-length range 0.3-1.1mm constitutes a good approach in order to obtain the mineralogical composition of the surface of asteroids. These data is compared to the spectral reflectivities of various types of powdered meteorites measured in the laboratory in order to provide a basis for chemical models and population distri-bution. Many different spectral types and mineral compositions are recognised among asteroids, but almost 75% of them appear to be similar to carbonaceous chondrites (which represent less than 3% of all meteorites recovered on Earth!). They consist of volatile-rich, low-density materials that probably condensed directly from the solar nebula at low temperatures. Another 15% of the asteroids seem to be composed of iron- and magnesium-rich silicate minerals with little dark carbo-naceous material. These asteroids may never have been melted, but metamorphic or condensation temperatures must have reached 850°C within relatively shallow layers, resulting in dense bodies. Relatively rare asteroids appear to be composed of solely metal (iron-nickel alloys), resulting from a molten state at temperatures exceeding 1400°C. Most of the metallic asteroids are 100 to 200 km in diameter and do not appear to be fragmented like the other types of asteroids. On the other hand, Apollo-Amor asteroids exhibit reflec-tance spectra similar to ordinary chondrites (70% of recovered meteorites), whereas main-belt asteroids do not. Both experimental studies of the effect of space environment on the optical properties of mineral grains as well as more refined spectral comparisons of asteroids with meteorites are required in order to gain a better insight into the physical properties and composition of asteroid types.

## Introduction

Asteroids have become objects of intense interest for planetary astronomers. They occupy the transition zone between the dense, volatile-poor terrestrial planets and the icy, gas-rich outer planets and satellites. Although a thorough understanding of the nature of asteroids is very important for science and because some of them may be potential impactors, we have not yet analysed directly any asteroid, either in situ or by sample return. Meteorites represent our best choice to know the physical and chemical characteristics of asteroids, but we do not know to what extent the information revealed by meteorites is representative enough. Therefore we need to obtain additional data using telescopes on Earth. Spectroscopy is particularly important in the study of the small bodies in the solar system such as asteroids and comets because we will never be able to visit or to collect pieces of every one. Reflectance spectroscopy constitutes a good approach in order to obtain the mineralogical composition of the surface of asteroids. These data is compared to the spectral reflectivities of various types of powdered meteorites measured in the laboratory in order to provide a basis for chemical models and population distribution. Many different spectral types and mineral compositions are recognised among asteroids, but almost 75% of them appear to be similar to carbonaceous chondrites (which represent less than 3% of all meteorites recovered on Earth!). They consist of volatile-rich, low-density materials that probably condensed directly from the solar nebula at low temperatures. They are believed to be rubble-pile, high porous bodies. Another 15% of the asteroids seem to be composed of iron- and magnesium-rich silicate minerals with little dark carbonaceous material. These asteroids may never have been but metamorphic or condensation melted, temperatures must have reached 850°C within relatively shallow layers, resulting in dense bodies. Relatively rare asteroids appear to be composed of solely metal (iron-nickel alloys), resulting from a molten state at temperatures exceeding 1400°C. Most of the metallic asteroids are 100 to 200 km in diameter and do not appear to be fragmented like

the other types of asteroids. On the other hand, Apollo-Amor asteroids exhibit reflectance spectra similar to ordinary chondrites (70% of recovered meteorites), whereas main-belt asteroids do not. Both experimental studies of the effect of space environment on the optical properties of mineral grains as well as more refined spectral comparisons of asteroids with meteorites are required in order to gain a better insight into the physical properties and composition of asteroid types and, specifically, to identify the source of ordinary chondrites, which are the most common type of meteorites striking our planet.

# Reflectance spectroscopy and chemical interpretation

Asteroid reflectance spectroscopy analyses the sunlight reflected off of the surfaces of asteroids, and can be used to determine the average composition of the asteroid surface. When light is reflected off of an asteroid, its spectrum is changed because the sunlight incident on mineral grains is transmitted to some depth within before being reflected. The mineral absorbs part of the spectrum and reflects part due to its molecular nature. The compositional interpretation of reflectance spectra for meteorites and asteroids is based upon the principles of molecular and crystal field theories. The success of remotely sensing the composition of asteroid surfaces rests on the fact that there are well-characterised absorption bands in the visible and near-infrared regions of the electromagnetic spectrum. These absorptions are diagnostic of the presence of rock-forming minerals from which cosmochemically significant inferences can be made about the evolution of materials during and after solar system formation (Pieters and McFadden, 1994; Moroz et al., 2000). Based primarily on meteorite studies, the origin of asteroid mineral assemblages should be likely derived from the solar nebula and survived intact, or thermally and/or aqueously processed after formation during the first few hundred million years of solar system evolution (Llorca and Brearley, 1992). Therefore, the most common components of asteroid surface materials are pyroxene, olivine, phyllosilicates, organic material, and opaques, which includes ironnickel metal, graphite, troilite, and magnetite. The combinations of these minerals on any particular asteroid surface reflect the formation and postformation processing to which the asteroid has been subjected. Conceptually, one should be able to mix together the spectra of this major minerals to form the spectra of a given asteroid. A mixture of various materials should exhibit weighted properties of each, thus allowing not only the identification of individual components but also an estimation of their abundance. Linear mixing procedures are

frequently used when modelling asteroid spectra with mixtures of meteorite spectra (Hiroi and Takeda, 1991).

# Taxonomy of asteroids

Meteoriticists and astronomers have developed independent classification procedures for meteorites and asteroids. Meteorites have been classified in groups and subclasses by chemical, mineralogical, and petrographic criteria based on laboratory analyses, whereas the classification scheme for asteroids is based on spectral characteristics. The most frequently used class designation adopted for asteroids is defined by a tree algorithm using 8 color extended visible data and albedo information developed by Tholen (1984). The main classes are:

**A type**: Very few have been discovered and are believed to contain an abundant amount of olivine.

**C** type: Approximately three-quarters of the asteroids belong to this category. They appear to be similar to the carbonaceous chondrites, the most primitive materials in the solar system.

**D** type: Redder in colour than the P-type asteroids, remain a mystery.

**E type**: Contain a high concentration of enstatite.

**M type**: Rare, constituted by iron-nickel alloy.

**P type**: Red colour, no composition is assessed.

**S type**: They represent 15% of the total population and contain silicate minerals pyroxene and olivine as well as iron-nickel metal. Related to the ordinary chondrites.

In spite of this largely unrelated taxonomy schemes, new studies are currently addressed in order to unravel which asteroids are the parent bodies of the different types of meteorites studied in terrestrial laboratories. The relevance of the classification scheme to the scientific endeavour is dependent on the degree to which it represents discrete compositional groups. Another fundamental question is if there are small bodies in the solar system which are not represented in the meteorite collection, and how abundant such bodies may be. The case of Vesta, the third largest asteroid (discovered in 1807), is unique. Its surface spectral reflectance indicates that it is likely the parent body of all basaltic achondrite meteorites, that is, howardites, eucrites and diogenites, the HED group (Drake, 2001). Indeed, observations carried out by the Hubble Space Telescope have lead to the discovery of a 460 km impact basin, which in turn supports the idea that Vesta is responsible for the birth of the so-called Vestoids. This is a cluster of V-type asteroids extending from the regions surrounding Vesta (at 24 AU.) to the edge of the chaotic 3:1 resonance at 2.5 AU, where can be rapidly transferred to Earth crossing orbits.

The surface composition of asteroids varies on average with respect to the distance of their orbit

from the Sun. The more distant ones have more water and carbon on their observable surfaces, whereas asteroids whose orbits are closest to the Sun tend to be more stony-iron on the surface. However, this is only the average, and some of the families of asteroids are strikingly at variance with their surrounding populations (Carvano et al, 2003).

# CCD spectroscopy

The introduction of CCD spectroscopy to asteroid studies has greatly advanced our ability to characterise the spectral reflectance properties of asteroids over the visible wavelength region of 0.4 to 1.0 µm. The high quantum efficiency CCDs allows for spectral measurements of asteroids much fainter than had been previously possible. CCD spectroscopy is capable of recording the entire spectral range in a single exposure, thus avoiding many complications associated with multi-filter photometry that can arise from the inherent rotational properties of asteroids or from temporal variations in sky conditions. Visible-wavelength asteroid spectra can be grossly characterised by the presence or absence of three prominent features: a 1 µm silicate absorption band, a sharp ultraviolet drop-off shortward of 0.5 µm, and an overall spectral slope that can range from moderately bluish to extremely red in colour. But the increased sensitivity and higher spectral resolution provided by CCD spectroscopy have revealed a number of more subtle features. The most notable of these is a shallow absorption band centred near 0.7 µm that is observed in the spectra of many primitive C-type asteroids and can be attributed to the presence of phyllosilicates (Vilas et al., 1993). More recently, an absorption feature centred near 0.49 mm is believed to indicate the presence of troilite (FeS). To date, more than 1500 reflectance spectra of asteroids have been acquired with the aid of CCDs (see Xu et al., 1995). A detailed analysis of this survey reveals that as smaller asteroids are sampled, continua are formed in the apparent strengths of absorption features, bridging gaps between previously separated spectral classes.

# Space weathering

The term *weathering* is borrowed from the geological processes of erosion and degradation caused by air and water. As used here it means surface alteration in outer space. In this environment, ions and micrometeorites take the place of air and water. Asteroids, as well as other planetary materials, are in a harsh environment and their surface are affected by micrometeorite bombardment, hard radiation, solar wind implantation, shock, and many other processes. We

are now beginning to understand space weathering processes and how they affect lunar soils and interplanetary dust. However, problems lie in extrapolating these processes to the asteroids and predicting their effects on optical properties. Galileo spacecraft images of asteroids 951 Gaspra and 243 Ida and Near-Shoemaker studies on asteroid 433 Eros revealed dramatic evidence that the surfaces of asteroids undergo alteration (Bell et al., 2002; Murchie et al., 2002). Unfortunately, a straightforward extrapolation of the lunar model of surface alteration can not explain the asteroid data, and spectroscopic data from asteroids are not consistent with lunar-like space weathering effects. This means that a new and different model for asteroid space weathering that is sensitive to asteroid composition needs to be developed (Clark, 1996). In an effort to simulate space weathering processes that may affect asteroid surfaces, several experiments aimed at understanding chemical changes due to irradiation effects on minerals and their possible correlation with reflectance changes are being conducted (Sasaki et al., 2001). Space weathering results in a darkening and reddening of asteroid surfaces with time. Space weathering has been proposed to explain spectral mismatches between asteroid types and meteorite classes, especially S-type asteroids and ordinary chondrites. In that sense, it is interesting to note that multispectral observation of S-type asteroid Ida by the Galileo spacecraft demonstrated that relatively fresh crater interiors or ejecta show colour properties similar to ordinary chondrites (Chapman, 1996). Spectral changes caused by space weathering on S-type asteroids seem to be related to the production of nanophase iron particles by micrometeorite impact heating.

# Asteroid mining versus impact hazard

Asteroid reflectance spectroscopy can be used for supporting mining purposes as well as for deflection of small but dangerous asteroids from Earth. Changing how much heat a hazardous asteroid radiates would change how it drifts in its orbit because of the Yarkovsky effect (Spitale, 2002). The idea is to change a threatening asteroid's surface temperature so that its orbit veers away from Earth. Possible schemes include covering the upper few centimetres of the asteroid with dirt, or painting its surface white, or fusing part of its surface with a spaceborne solar collector, all technically feasible and civically preferable to nuclear weapons. Reflectance launching spectroscopy would thus be required for monitoring changes in asteroid reflectance properties. As regards mining, some asteroids are quite attractive for their metals, and the volatile-rich ones would improve the economics of retrieval by on-site fuel

propellant production. Water could also be broken down into hydrogen and oxygen to form rocket engine propellant. Reflectance spectra data for hundreds of NEOs is gleaned to narrow the field to worthwhile candidates.

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# A QUICK LOOK AT SOME NEW STAR CATALOGS

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Some new astrometric star catalogs have recently become available, among them the Guide Star Catalog 2.2 (GSC 2), the USNO-B1.0, and the USNO CCD Astrograph Catalog 2 (UCAC 2). Both the GSC and the USNO-B are based on data collected from scanning photographic plates from the Palomar and Southern Sky Surveys. Positions in the UCAC, on the other hand, are derived from recent CCD observations, and proper motions are calculated from various earlier epoch data. A comparison of the features of these catalogs is presented, and results obtained with these catalogs on a few sample images are compared.

#### Introduction

In the past few years, most observers using CCDs for astrometric observations of minor planets and comets used the USNO-A2.0 star catalog [1, 2] (or the USNO-SA2.0, a subset of the former) as the primary source of reference star data. This catalog, however, is only the interim result from the efforts by the US Naval Observatory (USNO) to compile a star catalog that incorporates the information extracted from scanning the images of both the first and the second generation photographic sky surveys. The first version of the final result, the USNO-B1.0 catalog [3], is now available, effectively replacing the USNO-A2.0.

Contemporaneously, a second generation of the Guide Star Catalog (GSC), also based on scanned photographic plates from the sky surveys, is created at the Space Telescope Science Institute [4], and an intermediate release, the GSC 2.2, is already available online.

Finally, another star catalog, called USNO Astrograph CCD Catalog (UCAC) is under preparation at the USNO [5]. Contrary to the USNO-B and the GSC, this catalog is not based on scanned photographic images, as the positions are derived from current CCD observations. Although the observations are still under way, a second, intermediate release, the UCAC 2 [6], has recently become available.

We will first describe some basic properties of these new catalogs that are of interest for astrometric observers. The properties of the USNO-A2.0 are also described for comparison, as this catalog is well known.

## USNO-A2.0

The USNO-A2.0 provides positions and magnitudes (in B and R) of 526,230,881 objects, based on digitized images from the first Palomar Observatory Sky Survey (POSS I) from the north celestial pole to a declination of -30°, and on the

Science Research Council (SERC)-J survey as well as the European Southern Observatory (ESO)-R survey in the south. Only objects that were detected on both the blue and red plate were included in the catalog. The positions are good to  $\pm 0.25$ " at the plate epoch. For POSS I, the mean plate epoch is ~1957, and as the catalog does not include proper motions, some positional errors are can be expected for current epochs.

#### USNO-B1.0

In addition to the surveys plates used for the USNO-A catalog, the USNO-B also includes data from digitized photographic plates of the second Palomar Sky Survey (POSS II), the Anglo Australian Observatory (AAO)-R and the SERC-R surveys, as well as the SERC-I survey. This means that, for the sky north of -30° declination, five images (blue and red plates from POSS I, as well as blue, red and near-infrared plates from POSS II) at two epochs are available. In the south, four plates (the first generation ESO survey in red light, as well as the second generation blue, red and near-infrared images from the SERC and AAO surveys) were available. All objects detected on at least two of the available plates were included in the catalog, increasing the number of objects to 1,042,618,261.

With data from two separated epochs, it was also possible to calculate proper motions for the objects in the USNO-B catalog. The proper motions are relative, calculated for each plate so that the mean of the motions on the plate is zero. It should be noted that this results in small, systematic errors compared to proper motions that are measured against the fixed celestial reference frame.

The USNO-B is said to be complete to magnitude 21, but also includes information on many fainter stars. Positions are good to  $\pm 0.20$ " at current epochs. Besides positions and proper motions, the catalog lists magnitudes (separate for each survey, so there are up to two blue, two red and one infrared magnitude listed), stellar/nonstellar indicators, and other data for each object. Data for

brighter stars, which are heavily overexposed on the sky survey plates, are inserted from the Tycho 2 catalog.

#### GSC 2.2

Construction of the full GSC II catalog is still in progress, but an intermediate release, the GSC 2.2, is already available. It gives positions and magnitudes (in B and R) as well as stellar/nonstellar indicators for 455,851,237 objects. The data is based on digitized photographic images from the second generation sky surveys (that is, the POSS II north of -30° declination, and the SERC and AAO surveys in the south). A limiting magnitude of 18.5 in R and 19.5 in B has been set to ensure the photometric quality of the released data. Similar to the USNO-B, information for brighter stars are taken from the Tycho 2 catalog.

Positions are good to  $\pm 0.20$ " at the plate epoch. Although the GSC 2.2 does not include proper motions (except for the Tycho 2 stars), positional errors at current epochs should be smaller than for USNO-A due to the more recent epoch of the second generation surveys (~1993 for POSS II).

The final version, GSC 2.3, is expected to be released later in 2003. It will include information from the first generation sky surveys, as well as the Quick-V survey, and it will also contain proper motions. [7]

# UCAC 2

Contrary to the catalogs described above, the UCAC is not based on digitized photographic images, but the positions are derived from recent CCD observations. Between 1998 and 2001, the 0.2m astrograph of the USNO, equipped with a 4k x 4k CCD camera, was set up at the Cerro Tollolo Interamerican Observatory (CITO) in Chile, imaging the southern sky. In late 2001, the instrument was relocated at the Naval Observatory Flagstaff Station (NOFS) in Arizona. Observations of the northern sky are still under way, and will probably be finished by the end of 2003.

The second, intermediate release, the UCAC 2, has recently become available. It includes data on about 50 million stars in the magnitude range between  $8^{mag}$  and  $16^{mag}$ , and covers the sky from the south celestial pole up to a declination of about +45°. Proper motions are calculated from older epoch data, including the AGK 2, AC 2000, and several other catalogs, as well as from digitized images from the photographic sky surveys for fainter stars. The positions are good to about  $\pm 0.02$ " for brighter stars, ( $10^{mag}$  to  $14^{mag}$ ) and to  $\pm 0.07$ " for stars at the catalogs limiting magnitude. Magnitudes, intended for identification purposes only, are given in a single, non-standard colour.

## Observations

Observations of two fields around visible-light counterparts of sources in the International Celestial reference Frame (ICRF) [8] were performed with a SBIG ST-6 CCD camera at the 0.6m f/3.3 reflector of the Davidschlag Observatory near Linz, Austria (IAU Observatory Code 540). Astrometric data reduction of the images, using linear plate solutions for the 15' x 20' field, was done with the Astrometrica software, using each of the catalogs described above.

The first field was centered at the quasar ICRF J084205.0+183540. A total of ten images, each a 120 second integration taken on 2003 February 19, were measured, resulting in detections of the quasar with a peak SNR of about 40. The results of the reference star fits are summarized in Table 1: The number of reference stars found in the catalog is listed in the column "Total". Stars with residuals larger than 1" in either Right Ascension or Declination were rejected by the software. The column "Used" lists the number of reference stars that were used in the final solution (i.e., having residuals less than 1" per coordinate). The mean residual for these reference stars in each coordinate is given in the last two columns of Table 1. The numbers shown here are the mean values from the ten available measurements.

Catalog	Total	Used	dRa	dDe
USNO-A2.0	123	109	0.28	0.28
USNO-B1.0	133	115	0.18	0.18
GSC 2.2	113	110	0.18	0.17
UCAC 2	17	17	0.06	0.08

Figure 1













# Figure 4

Plots showing the reference star residuals found in a typical image from the series are presented in *Figures 1 to 4*: The first figure shows the residuals from the USNO-A2.0 catalog, the second from the USNO-B1.0, the third from the GSC 2.2, and *Figure 4* shows the reference residuals from the data reduction with the UCAC 2. Obviously, the scatter in the reference star positions improves notable when switching from the USNO-A to the USNO-B or GSC II catalog. The UCAC does even better, although the comparable high limiting magnitude results in a rather small number of available reference stars.



Figure 5



Figure 6



Figure 7





Figures 5 to 8 plot the reference star residuals for both for Right Ascension (blue) and Declination (green) against the peak SNR of the star. The red lines show the expected uncertainty in the measured position for the stars [9], where the light red line represents the two sigma, and the dark red line represents the three sigma error level. In Figure 5, which shows the data from the measurements using the USNO-A2.0 catalog, significant scatter can be seen even for very bright reference stars. In Figure 6, which shows the values found using the USNO-B1.0 catalog, the scatter in the reference star positions closely follows the expected uncertainties from the centroiding. Figure 7, showing the residuals from the data reduction with the GSC 2.2, is similar, with a few outliers, probably due to the missing proper motions in that catalog. Figure 8 shows the same plot for the UCAC 2: While the faint stars, for which larger errors can be expected, are missing in that catalog, the available reference stars show residuals dominated by the predicted centroiding errors.

One should note, based on the reference star residuals, only conclusions about the internal precision of a catalog can be drawn. Any systematic errors will go unnoticed. For that reason, the position of the ICRF source in the centre of the filed has been measured, and compared with the position given in the ICRF catalog [10]. The results are summarized in Figure 9: The USNO-A2.0 shows the largest residuals, with a mean difference of about 0.44" between the position measured from the images, and the coordinates listed in the ICRF. Both the USNO-B1.0 and the GSC2.2 give comparable results, with a total residual of about 0.15". The measurements based on the UCAC 2 have the smallest error, with an offset of only 0.09". The error bars in *Figure 9* indicate the standard deviation from the mean position as found by measuring all ten available images.



# Figure 9

The second field was centered at the BL Lac object ICRF J082057.4-125859. A total of five images, each a 120 second integration taken on 2003 March 24, were measured, resulting in detections of the object with a peak SNR of about 20. The results of the reference star fits are summarized in Table 2 (where the columns have the same meaning as in Table 1). Again, the numbers shown in this table are the mean values from the five available measurements.

Catalog	Total	Used	dRa	dDe
USNO-A2.0	415	374	0.20	0.23
USNO-B1.0	474	384	0.17	0.21
GSC 2.2	440	406	0.14	0.18
UCAC 2	99	98	0.05	0.09



Figure 10



Figure 11







# Figure 13

Plots showing the reference star residuals for this field are shown in *Figures 10 to 13*. While the improvement of the USNO-B and GSC II over the USNO-A is less obvious than in our first example, is it still noticeable. The UCAC 2 provides a sample of almost one hundred reference stars in that rich field, and the results are superior, again. The single outlier seen in this plot is a double star that was not resolved in the images used here.



Figure 14



Figure 15



Figure 16





The plots of the reference star residuals versus the peak SNR for the second field are shown in *Figures 14 to 17*. They show much the same patterns as the corresponding plots for the first field.





*Figure 18* shows the offset from the measured position of the optical counterpart of the ICRF source from the position given in the ICRF. The situation is very similar to the results obtained for the first field: The position based on the USNO-A2.0 shows the largest offset with a total residual of 0.26". The USNO-B1.0 and GSC 2.2 give similar results, with total residuals of 0.16" and 0.12", respectively, and the position based on the UCAC 2 is off by 0.10" only. The error bars in *Figure 18* indicate the standard deviation from the mean position as found by measuring all five available images.

#### Availability

The full USNO-B catalog is not generally available, and there are currently no plans to produce CDs, DVDs or any other hardware media for distribution. Parts of the catalog, however, can be downloaded from the Integrated Image and Catalogue Archive Service provided by the USNO at http://www.nofs.navy.mil/data/FchPix/.

The GSC 2.2 is also only accessible trough the internet. The GSC online query is hosted by the STScI at <u>http://www-gsss.stsci.edu/support/data\_access.htm</u> According to information on the GSC II web site [7], options for mass distribution of the final version (GSC 2.3) on some media are considered.

The UCAC 2 is distributed by the USNO on three CD-ROMs. For more information, please visit the UCAC web page at <u>http://ad.usno.navy.mil/ucac/</u>.

#### **Summary and Conclusions**

Three new star catalogs that are of interest to astrometric observers have become available recently, namely the USNO-B1.0, GSC 2.2, and the UCAC 2. Two fields, containing objects used in the ICRF, have been observed, and astrometric data reduction has been performed using the three new catalogs, as well as the USNO-A2.0. Although comparison of only two fields is certainly not an extensive test by any means, the results obtained with the new catalogs seem to be very promising. Hopefully, the USNO-A2.0, which now seems to be obsolete, will soon be replaced by one of these new catalogs as the main source for astrometric standards used by most astrometric observers. Acknowledgements – The author wants to thank Erich Meyer from the Davdischlag Observatory for taking the images of the two ICRF sources, and is grateful to Dr. Nobert Zacharias from the USNO for providing pre-release data from the UCAC 2 catalogue for these two fields.

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# ASTROVIRTEL AND THE SEARCH FOR TROJANS OF OUTER PLANETS

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This report describes the current status of an on-going work, started in the frame of an approved ASTROVIRTEL program and pursued with an accepted proposal submitted to ESO, for the cycle P70, having the aim to detect bodies orbiting around the Lagrangian points of the outer planets, analogous to the Jupiter Trojans. Till now, a large number of images taken with the WFI of the 2.2m telescope of ESO at La Silla has been examined. Although still unsuccessful in respect to outer Trojans, the search (given the designation I03 by the Minor Planet Center, in the following MPC) has already produced many new asteroids, some with interesting orbits.

#### Introduction

In year 2001 we proposed to ASTROVIRTEL a program aimed to find minor bodies orbiting in the Lagrangian points of the outer planets, founding our expectation on the theoretical and observational scenario expounded in the present paragraph. Indeed, the possibility of the existence of bodies in L4 and L5 of the three outer planets has been debated in the literature by several authors, who put forward different considerations regarding the stability of their orbits. In the following, we will call generically 'Trojans' these bodies.

The recent discovery of the first Neptune Trojan (2001 QR322) has triggered additional observational surveys aimed to search Trojans of the outer planets.

At present, more than 1600 minor planets have been classified as Jupiter Trojans: 1022 are in the preceding cloud L4, and 603 in the following L5 cloud. The most accredited hypothesis about their origin is that they are the remnants of the planetesimal swarm that populated the feeding zone of the proto-Jupiter during its growth.

There are various ideas on how planetesimals could have been captured as Trojans based on different physical processes. Shoemaker et al. (1989) collisions mutual proposed that between planetesimals populating the region around Jupiter orbit might have injected collisional fragments into Trojan orbits. Yoder (1979), Peale (1993) and Kary and Lissauer (1995) showed that the nebular gas drag could have caused the drift of small planetesimals into the resonance gaps, where they could have grown by mutual collisions to their present size.

The mass growth of Jupiter is also an efficient mechanism to trap planetesimals into stable Trojan orbits, as proved by Marzari and Scholl (1998a, b). The stages envisioned for the growth of Jupiter were presumably reproduced during the formation of Saturn and, as a consequence, the planet should have trapped local planetesimals as Trojans as well. The first high resolution survey (Chen et al., 1997) failed to detect any Saturn Trojan; however, selection effects or the low number of objects, compared to Jupiter Trojans, may have worked against the discovery. On the other hand, a critical aspect of the Trojan-type orbits of Saturn is that they are easily unstable. The first numerical experiments by Holman and Wisdom (1993) found stability areas for orbits with large libration amplitudes over timescales of 20 Myr. A work by De la Barre et al. (1996) proved that on longer timespans (400 Myr) only few orbits remain stable, thanks to their peculiar  $\omega$ -librating state. A study by Melita and Brunini (2001) located stable niches around the triangular points of Saturn where some primordial objects could have survived over the age of the Solar System. These niches are close to the ecliptic, and mostly with high libration amplitudes. Dynamical studies show that the stable Saturn

Trojans have values of libration amplitude (defined as maximum oscillation amplitude of the angle  $\lambda T - \lambda S$ ) between 50 and 80 degrees. For inclinations higher than 20°, Saturn Trojan orbits become rapidly unstable on timescales shorter than 1 Myr (Marzari et al. 2002; Nesvorny, D. and Dones, L., 2002).

More controversial is the theory of Uranus and Neptune Trojan capture, because the formation process of the two planets is not well known. It has been proposed that the proto-Uranus and Neptune formed through an initial buildup of a core prior to the accretion of a gaseous envelope in the solar nebula environment, on a timescale of the order of 107 years (Bryden et al., 2000). Close encounters between left-over planetesimals and the core would have led to orbital drift and migration of the two planets into inner orbits. In this scenario the capture of local planetesimals as Trojans may have occurred in the final phase of growth of the two planets, but it is crucial to understand whether Trojan orbits would have been stable during the subsequent phase of orbital migration. Fleming and Hamilton (2000) and Gomes (1998) have shown that a low or moderate migration would not completely destabilize Trojan orbits.

According to Thommes et al. (1999), Uranus and Neptune did not form in their present location, but instead in the region between Jupiter and Saturn at the same time of the two giant planets. When Jupiter and Saturn accreted the nebular gas, the proto-Uranus and Neptune were gravitationally scattered outwards, because of the high gravitational strength of the two proto-planets. In this context, primordial Trojans could not have survived the phase of scattering by Jupiter, but they may have been captured at subsequent times in temporary stable orbits from the steady flux of comets from the Kuiper Belt (Rabe 1954, 1972).

As shown by the above short summary, it is clear that the discovery of Trojans of the outer planets would have a strong impact on the understanding of process of planetary formation, in particular for Uranus and Neptune. Based on these considerations, we have been granted access to the Astrovirtel data base in order to examine images taken with a variety of telescopes, including the Hubble Space Telescope.

Up to now, we have analyzed, by using dedicated codes, almost all the ESO 2.2m telescope WFI images received from the Astrovirtel Archive and 66 new images taken in February 2003, extracting about 2300 positions of known and new objects, mostly many Main Belt asteroids. We detected in particular three Jupiter Trojans candidates and one TNO.

#### The WFI images

In order to properly search the Astrovirtel archive, we preliminarily decided to select all the WFI image triplets which fell at a given date into a box of  $60^{\circ} \times 60^{\circ}$  around the Lagrangian points L4 and L5 of Saturn, Uranus and Neptune (having three images of the same field allows to search for moving targets using well proven methods). Notice that the WFI images were taken originally for purposes completely different from ours, so that it is quite difficult to find three images having all the requirements for bona fide detections of Trojans, e.g. with the same broad-band filters and same (long) exposure times. In order to reduce the problem to a tractable one, the ASTROVIRTEL team developed a specific software (listator2 web interface), in order to allow a search taking into

account our special requirements (positions, dates, filters, exposure times, etc.).

In June 2002, we finally received 14 DLT tapes containing the images satisfying those criteria (see Table 1). There are in total about 3500 images, the oldest dating back to 1999, but only 30% of them are scientific images, while the rest calibration files. As about the new dedicated images (taken for the cycle P70, in February 2003), they are all around L5 of Saturn, taken with the same exposure time (1000 seconds) and the same V filter.

In *Fig. 1*, the sky coverage corresponding to the images retrieved in the archive is shown. The figure shows the offset of the frames with respect to the position of Lagrangian points (L4 and L5) of each planet. The offset has been calculated considering the position of the Lagrangian points at the date of which each image has been taken.

The WFI images consist of a mosaic of 8 chips; the scale is 0.238 arcsec/px, the total field of view (with gaps) is  $34' \times 33'$  ( $8250 \times 8196$  pixels), so that a preliminary heavy work of image composition and flat fielding was absolutely mandatory. In the following paragraph we give some details of the overall procedure.

Number of DLTs (≈ 40 Gb/DLT)	14
Total amount in Gb	≈560 Gb
Total number of images	3555
Scientific images	1066 (≈30%)
DLTs already analyzed	11
Scientific images already analyzed (till the end of the procedure)	830

Table 1 - Details of WFI images



Figure 1- Sky coverage corresponding to the images retrieved in the archive. The figure exhibits the offset of the frames with respect to the position of L4 and L5 of each planet. The offset has been calculated considering the position of the Lagrangian points at the date of which each image has been taken.

#### **Reduction of the Mosaic frames**

The software packages used in our work are:

*mscred*: it runs under iraf, and it can handle mosaic images;

*wfpdred*: this code has been written by a group of astronomers of the Observatory of Padova (Rizzi, 2003); it assembles in a unique frame the 8 parts, in which the raw WFI images are divided;

*fitsblink*: this software has been written by a group of researchers from the Èrni Vrh Observatory (Skvarè, 2002). It detects possible candidates for asteroids, based on their movements with respect to stars field. It also gives the possibility to recognize known asteroids by using a database containing all of them (this database is continuously updated via the MPC). The already known asteroids are marked on the display in a different way for easy visual recognition;

*Amigo*: a fortran code, which produces a distribution of asteroid's velocities as projected on the sky (namely velocity in RA and Dec) for any given direction of the line of sight at any date. As shown in the example (see Fig.2), sometimes the separation of the different classes of objects is quite distinct. Therefore, by using this code for each image, we are able to quickly identify different regions in the RA-DEC velocity plane corresponding to different groups of asteroids, like Main Belt, Jupiter's Trojans, Saturn's Trojans and so on.

The routine process is carried out in several steps.

1 - In the first one, we correct images by flat field and bias, using the mscred package. Then we assemble the 8 parts, in which each image is divided, in order to produce a single image, instead of a mosaic one. We need to do this, because the software packages used in the following steps can't handle mosaic images. This part of the work is done by using the *wfpdred* package. After this step, we filter the images, if needed, with a median filter, in order to remove bad pixels and cosmic rays, as much as possible. A special procedure had to be implemented for the many Iband images, which shows conspicuous fringing. We are indebted to Dr. Monelli (Rome Observatory) for his kind help in solving the problem.

2 - Before the usage of *fitsblink*, the images have been binned (2x2) and cut into 8 parts, in order to speed-up the subsequent analysis. At this stage, we are ready to detect moving objects, using *fitsblink*. We choose three images corresponding to the same sky field, preferably with (almost) the same exposure time. The images do not need to be taken in the same night, because *fitsblink* can handle images taken in different days, for example about 24 hours apart. Such a choice is useful for the detection of very slow moving objects, such as the sought-for Uranus' and Neptune's Trojans.

In its first passage, for each of the 3 images *fitsblink* creates a catalog of bright sources. These catalogs are compared with the appropriate section

of the USNO catalog, in order to recognize real stars, to make a good astrometry and to estimate the calibrated magnitude of all extracted objects.

The stars are then cut off from these 3 lists of sources; the remaining objects represent all possible asteroid candidates. From these 3 lists the software extracts objects that are moving along a linear path with a constant velocity, namely that describe a short arc of the orbit of a possible real object.

3 - The last step of the search is done visually, we have to confirm by eye if the candidate objects are real or if they are false detections. During this phase we are automatically advised if the detected objects are new or already in the MPC data base, because the software marks them with a different symbol. Once we decide they are real, we record their positions and estimated magnitudes on a file written according to the MPC format. These files are then sent to the MPC for the calculation of the orbit.

Three positions are in principle sufficient to derive a preliminary orbit, but more are needed to calculate a well defined one. So we look for other images taken in the same field, during the same days or a few days later, in the available database.



Figure 2 - This image represents the distribution in velocities of the asteroids observed at a certain date in a given line of sight, as produced by Amigo code. In this field there are two Jupiter Trojan candidates and one TNO (marked by red arrows). There are also other two interesting objects (marked by blue arrows) in the region where the distributions of main belt and Jupiter Trojans velocities overlap. The two points marked with blue circles may correspond to Near Earth Objects.

At this point, we calculate projected velocities (in RA and DEC) of all moving targets in order to have some immediate information about their nature. We also generate a plot for the expected distribution of velocities in that field at that date, using the AMIGO code. In this way, we are able to distinguish, at least in favorable cases, between interesting objects and non interesting ones (normal Main Belt). Indeed, for some dates and fields different groups of asteroids are well separated in the RA-Dec velocity plane (see Fig. 2). For these cases, if we superimpose the detected objects to the RA-Dec velocity plane, we immediately see which

group they could belong to, but of course we cannot be sure if they are real members of a particular group. In effect, some groups of asteroids, such as NEOs, can be more or less everywhere in this plot. In other words, with the help of such plots we can be sure that if an object lies outside of the regions corresponding to Trojans, it will not be a Trojan; but if an object belongs to the region of Trojans we cannot conclude that it is surely a Trojan. A proper orbit will always be needed.

This methods works well essentially at opposition and in quadratures, at intermediate angles all classes more or less overlap (see Fig. 3). Notice that for a given direction of view, not all the Lagrangian regions are simultaneously visible and hence they are not included in the plots, as in Fig. 2.



Figure 3 - A case of overlapping velocities (Saturn L5, Uranus L4, Neptune L4 are along the same line of sight, and the projected velocities are partly identical). Of the many objects found by our survey in this field, the majority look Main Belt asteroids; there are though 4 interesting objects, for which further data are highly desirable.

#### **First Results**

Out of the 1066 scientific WFI images selected from the Astrovirtel archive up to now about 830 archive images and all our proprietary images have been corrected by flat field and bias, processed with the *wfpdred* package, stored on DVDs and analyzed till the end of the procedure, including the visual check.

As a result we have already submitted to the MPC about 70 reports, containing approximately 2300 positions of more than 700 distinct asteroids, mainly belonging to the Main Belt. The faintest objects are around R = 24.0; there are also several fairly bright but not numbered objects (e.g. one has R = 15.9). The MPC has already awarded I03 about ninety preliminary designations.

In Fig. 4, the number of the detected objects vs. their velocities is shown, distinguishing the already known objects and the new designations. In the top panel, there is a comparison between all detections

and already known asteroids, while in the second panel new designations (obtained as all detected objects minus known detections) versus new designations are plotted. From the figure, we can see that slow objects are easy to detect. This is important because our primary targets are presumably slow objects.

At this stage, a statistical analysis of the material is fairly difficult, because we are using images taken with a variety of filters, exposure times and positions; at any rate, this analysis will certainly be worth doing with more data in the near future. Furthermore, our positions are used to improve the quality of the orbits.



Figure 4- Number of the detected objects vs. the velocity module. In the first picture (a) there is a comparison between all detections and already known asteroids, while in the second (b) new detections (which have been obtained by subtracting known objects from all detections) are compared to new designations.

## **Future work**

Several actions have still to be made or completed:

- 1. Finish the analysis of the remaining 3 DLTs.
- 2. We started to test the dependence of the velocity distributions on the solar elongation and the Earth's position, the preliminary results of maximum efficiency at opposition and quadratures of *Amigo* being subjected to closer scrutiny.
- 3. We are looking for images in other archives to improve our search program.

The correction of the 830 images till the *wfpdred* procedure took about 5 months (one person full time). In December 2002 we installed the *fitsblink* software, which became almost immediately ready for regular production work. In less than a month (including the vacation period) we could then process to the end 50 fields (one person full time). So we estimate that at the present pace and with the present human resources (one person full time), 9 more months of work will be needed to UPd to complete their share of work on the WFI images.

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# TRANSFORMATION OF THE BAKER-NUNN CAMERA OF SAN FERNANDO

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We present the transformation of a Baker-Nunn Camera (BNC) for remote and robotic use with a large format CCD, and its transfer to a new site located in Catalan Pyrenees. This project is a collaboration between the Fabra Observatory (Reial Acadèmia de Ciències i Arts de Barcelona) and the Real Observatorio de la Armada de San Fernando (ROA). Once refurbished, the 50cm f/1 camera will have a useful FOV of 5°x5° and will be controlled via Internet. This is not a restoration of an old astronomical facility but a completely innovative refiguring of the instrument. We will modify both its mechanics and optics and will set up a new unique facility in Catalonia operating in real robotic and remote mode. Once the BNC will be operating, our scientific project considers two kinds of observing programs: a systematic observing program (QDDS) and selective observing programs. The Quick Daily Sky Survey will operate by means of TDI (Time Delay Integration) CCD observation. It will be able to cover almost the entire northern sky in 4 or 5 nights up to V=20 producing up to 25 Gb/night of data. The other specific observing programs include the discovery and tracking of solar system objects (NEOs, PHAs, main belt asteroids, comets and TNOs), the detection of extra-solar planets, the detection of novae and supernovae, the quick localization of counterparts of GRBs, the detection of the camera.

#### Introduction

The Automatic Wide Field Telescope (AWFT) project (Núñez et al., 2002) is a San Fernando-Fabra collaboration to enable a Baker-Nunn camera for remote and robotic CCD use.

The original Baker-Nunn cameras (BNC) were f/1, 50cm aperture modified Schmidt telescopes originally created by Smithsonian Institution (Henize, 1957) to photographically observe artificial satellites. The superb optical design of the camera achieved a fast response (f/1) yielding out extraordinary useful field of view (FOV) of  $5^{\circ}x30^{\circ}$ with a spot size inferior to 20 microns throughout the field. This turned BNC into an extraordinary instrument in spite of its manually altazimutal movement and the use of curved 55cm cinemascope film as detector.

One of the BNCs was installed at the Real Instituto de la Armada de San Fernando (ROA) during the 60s. Once the photographic observation of satellites was relegated, the camera was donated to ROA, where it has been maintained inactive but in excellent state of conservation. In order to transform this BNC to a proper remote and robotic use with a large format CCD, an extensive optical and mechanical transformation project must be performed. After this refurbishment, the instrument will be moved to its new observing site in Tossa d'Alp Peak, in Catalan Pyrenees. It will operate from there as a quick reaction full robotic and stand alone facility observing in remote real time mode in order to follow the most appropriate scientific programs.

The experience of the ROA in the automatization of the Meridian Circles of La Palma (CAMC) and San Fernando (CMASF) operating from Argentina (Muiños et al., 2001) will guarantee the right performing of all the refurbishment stages. Besides, the nearly centenary experience of Fabra Observatory in high quality astrometic observations and the experience with the recent restoration and modernization of its own facilities ensure the right development of the project and the best scientific use of the transformed-BNC.



Figure(1). Baker-Nunn at ROA when it was still on active service.

## **Refurbishment project.**

Through a simple optical modification for adapting the camera for the use with CCD, we will achieve an useful FOV of 5°x5°. This provides us with a unique instrument to perform precise systematic observations of large sky areas in a reduced amount of time and to a relatively high limiting magnitude. Moreover, the camera and all other instruments involved in the observatory will be modified for operating as a totally automatic robotic and remote facility controlled via Internet.

The refurbishment project consists in the following phases:

• Mechanical modification and remote telescope control.

Conversion of original mount to equatorial, installation of new servo drive for RA and DEC axes, positional absolute encoders, multi-axe closed-loop controller and a GPS card must be implemented. These modifications are now being held at the military facilities in San Fernando.

• Optical modification.

CCD adaptation implementing a 4kx4k-9µm front-illuminated CCD with optional filters will be held. To maximize the useful FOV maintaining the low magnitude of aberrations we should modify certain optical parameters and add a field flattener 3-element corrector. A new precise optical design is currently being studied to achieve the best performance. • Software adaptation for telescope control system.

Adaptation and/or creation of software appropriate for our specific instrument and operating mode for both telescope working and observatory control. Own telescope movement, guidance and pointing software is available to be adapted to the new requirements in San Fernando. Dome, weather station and other observatory parts controlled by software are chosen to work with known available TCS.

• Building and observatory elements transformation.

Remodeling of the building, including dome, weather station and microwave telemetry and data link system installation at the chosen site can be done only at summer time because of high mountain climate.

Nowadays, there are two similar projects involving BNCs transformations. One of them, the Australian Automated Patrol Telescope project (Carter et al.), has already accomplished successfully those objectives. The other, held at the Rothney Observatory (Canada) is currently in the late stages of refurbishment project.



Figure(2). Mechanical transformation of the Baker-Nunn camera is being held in San Fernando, where they have consolidated experience with astronomic instruments.

# Scientific project

For such a fast response high FOV instrument we must consider two different kind of observing programs to be developed. First, an ingenious survey capable of optimize the BNC performance which has been chosen to be the Quick Daily Sky survey (QDSS). And besides, other specific observational programs of diverse nature related to different areas of astronomical and astrophysical interest.

Nevertheless, this division may not be always so clear since some specific programs could take advantage of the QDSS mode not only using its resulting data, but also enabling several real time data processing tasks and other possible interactions such as programmed automatic launch alarm systems.

# **Quick Daily Sky Survey (QDSS)**

The systematic observing program would operate by means of TDI (Time Delay Integration) CCD observation. This scanning technique consists in covering sky areas following celestial meridians towards the pole while the CCD charge is transferred at the same rate that the telescope is slewed. With the planned modified BNC FOV, would be allowed to cover daily up to 25% of the sky between declinations -30 < d < +70 up to more than V=20 mag.

Below we justify these numbers in a greater detail:

Let assume a BNC's useful FOV of 5°x5°. This could be covered approximately 4°x4° with a 4kx4k 9µm-pixel CCD, yielding an astrometric scale of 3.5 arcsec/pixel. Let's suppose, also, a TDI equivalent exposure time (time used by a star to cross the CCD chip in N-S direction) of 2 minutes. For instance, if we have a scanning speed of v=8 sqdeg/min=480 sqdeg/h and assume a 12h winter night ( $\Delta$ t=12h/night) therefore we can estimate the daily coverage as S=v·  $\Delta$ t=5760 sqdeg/night, which is about the 25% of the overall visible sky from the northern hemisphere.

Given the aperture of the BNC, a integration time of 2 minutes, the scale, and considering a CCD detector with moderate-high quantum efficiency (70%) offered by a typical commercial CCD camera, we estimate the limiting magnitude of the QDSS of at least V=20 mag. In this range there are many astronomical and astrophysical fields of research that could benefit from the obtained data.



Figure(3). Diagram of TDI operating mode. Once the CCD is oriented in N-S direction, the telescope moves covering sky areas following celestial meridians towards the pole while CCD charge is transferred at the same rate. TDI allows a wide coverage of declination with an improved magnitude limit (it depends on the readout rate chosen) with an easy synchrony to work.

## Specific observing programs

Apart from the systematic programs as QDSS, BNC will be able to operate specific programs of diverse nature. Extraordinary large FOV and quick reaction in remote-robotic mode enables modified BNC to work in observational programs such as:

 Discovering and tracking of NEOs, PHAs, MBOs, comets, KBOs and TNOs.
 A complete census of these objects is demanding for accurate calibration of Earthcollision probabilities (NEOs, PHAs) and of present models of solar system origin, composition and evolution (MBOs, comets, KBOs, TNOs).

Observation and tracking of comets and asteroids has been developed at Fabra and San Fernando Observatories for more than a century. BNC technical specifications will be ideal to enforce this activity since the extraordinary large FOV besides the ability of working within a wide range of temporal resolution will greatly increase the probability of detection and discovery.

- Detection of extrasolar planets. Photometric transit technique applied over a large FOV is likely to bring positive detections since it greatly increases the number of measured stars and, consequently, the probability of spotting transit
- Detection and monitoring of optical transient events such as gamma ray bursts (GRBs), supernovae (SNs) and novae.

Again, the BNC large FOV combined with its planned fast slewing response will permit to point the GRB afterglow few tens of seconds after satellite alarm has been given.

- General and temporal high-resolution CCD photometry in scanning mode. The use of the filters added to the modified BNC during scanning modes (both QDSS and non-QDSS scanning) will permit to cover large areas of sky within a wide range of time resolution in selected wavelength range.
- Discovery and tracking of space debris (0.1m-1m).

A complete orbit catalog and tracking of these objects is demanding, since they can put in danger current or future space missions.

#### Data flow and processing

BNC operations will generate a large amount of data to be transmitted, processed and archived. The proper flow, processing, analysis, archiving and retrieval of such huge amount of data will be another challenge of this project. For instance, only QDSS data would produce up to 12 Gb/night.

Managing of this amount of data for real time remote operations require a fast data flow. In our project, it will be trough microwave technology from the high mountain top site chosen to the Catalan universities fast speed network.

Specifically, the processing and following use of the data would go through the following steps:

- 1. Immediate and in situ processing.
  - Basic image handling, automatic search for minor bodies (NEOs, MBOs, TNOs,..), supernovae (SNs), novae, gamma-ray bursts (GRBs), extrasolar planets... or programmed automatic launch alarm systems.
- 2. Short term processing.
  - Includes not only data transfer, storing and archiving and the usual knowledge discovery through traditional data processing, but also other more sophisticated digital processing techniques of reconstruction, fusion,...
- 3. Mid and long term processing.

Besides the storage of raw data, all the developed data should be passing through an efficient image compression system and be available in some kind of permanent archiving with access from some international astronomical databases coordinated group. Site

In order to take advantage of the BNC specifications, this should be moved to a site with very good astronomical conditions. We have chosen the Tossa d'Alp Peak ( $\phi$ =42:19:14.7N,  $\lambda$ =1:53:40.7E, h=2531m) located Catalan Pyrenees in a natural park protected by law 100 km north from Barcelona. This place shows excellent sky conditions: darkness, moderate humidity and seeing, low extinction, good transparency.... In addition, we have two independent meteorogical data of the place for the last 5 years.

Moreover, it provides us a lot of very valuable facilities such as guaranteed round year access, electricity, water, telephone and a guarded building to harbour the observatory next to a mountain refuge with all year round guard living in.

And finally, it must be remarked that it is already a very touristic place with more than 20000 visitors during summer and even more during sky season. That would allow us to continue the long tradition and experience of Fabra Observatory in educational and spreading activities during the daily hours.



Figure(4). Tossa d'Alp Peak. The building behind the mountain refuge will be transformed to harbour the observatory.

#### Conclusions

Automatic Wide Field Telescope (AWFT) has been presented and described as the project of transformation a BNC into a fast high FOV remote and robotic CCD stand-alone facility operated through internet, its placement at a new location and the following use of the instrument for scientific purposes.

Finally, we must remark that this project does not have a character of restoration of an old facility to equip it with the new instrumentation, but it consists in a completely innovative refiguring of the instrument for achieving such special specifications for a successful developing of the relevant scientific tasks described.

# Acknowledgements

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# JOHNSON V-BAND PHOTOMETRY OF MINOR PLANETS BASED ON THE HIPPARCOS CATALOG:

An observing methodology for determining accurate magnitude - phase angle parameters

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Physical classification of asteroids would greatly benefit from an expansion of current magnitude-phase angle observations to include many more objects than to date, and to extend coverage to small phase angles. A proposal is put forward for a CCD observing methodology which exploits the precision photometry of the Hipparcos Catalog to yield accurate Johnson V-band photometry of asteroids.

The approach is to reference CCD images of asteroids relative to images of Hipparcos stars, selected to meet the criteria: 5.0 < V < 9.5 and +0.2 < (B-V) < +1.0. Images of both are taken either with the same camera or, preferably, using a second CCD camera attached to a shorter focal length / small aperture telescope or lens. It is recommended that the CCD camera used has a 'pseudovisual' spectral response similar to the S20 photocathode as used on the Hipparcos satellite and that it is used unfiltered.

Calibration of the CCD camera calls for an accurate determination of the transformation coefficient for conversion from the instrumental magnitude system of the camera to the Hipparcos, Hp magnitude system. The author also demonstrates that the read-across from Hp magnitude to Johnson V magnitude can be carried out with an accuracy of much better than 0.004 mag based on Landolt or E-region standard stars.

#### Introduction

The recent advent of the CCD camera as an observing tool has led to a rapid growth in the number of asteroid discoveries and known rotation rates. Amateurs are contributing in both these areas. Statistical analyses of asteroid rotation rates can now be carried out based on sample sizes in excess of 1000 objects thanks to a significant contribution from differential photometry by amateurs equipped with CCD cameras and small telescopes in the aperture range of 10 - 40 However, although differential centimeters. photometry is a powerful technique for establishing the shape of the lightcurve, there is a drawback in that it is generally based on a comparison of brightness relative to field stars, typically Tycho or GSC stars, which happen to be in the CCD frame when an exposure is taken. Since the field of view is commonly restricted to areas much less than one square degree, such comparison stars are often relatively faint and do not usually allow for accurate photometry against the standard Johnson or Cousins magnitude systems. One consequence of this limitation is that most observers are not able to construct an accurate magnitude - phase angle relationship from their data, and so are not contributing to our knowledge of photometric phase effects, which reflect the physical nature of the surface, including roughness and porosity.

A chapter of the recent *Asteroids III* book is devoted to a review of '*Asteroid Photometric and Polarimetric Phase Effects*', in which Karri Muinonen and others describe our knowledge to date and point out that the physical classification of asteroids would greatly benefit from an expansion of current magnitude-phase angle observations to include many more objects, and to extend coverage to small phase angles. At present, sub-degree phase-angle measurements have been carried out for only about 20 asteroids and the large majority of the slope parameter, G values quoted in the literature are not the result of direct measurement but rather are empirical estimates based on asteroid type and albedo. Figure 2 is taken from Asteroids illustrates magnitude-phase III and angle relationships for 7 bright asteroids. Subtle differences exist between the form of these relationships and minor planet classification type. Clearly, much more needs to be done to quantify these properties and I hope that the methodology set out here will encourage a number of amateurs to take up this challenge.



Figure 2

# Proposed methodology

So how do we achieve this? A key requirement to enable CCD observers to achieve precision absolute photometry is a set of reliable reference stars. The Johnson-Cousins BVRI magnitude system is in effect defined by a set of several hundred standard stars, which were observed repeatedly by Landolt and Cousins. However the large majority of these stars lie close to or south of the celestial equator and so are not a practical option. The most comprehensive broad-band photometry available to date is that carried out by the Hipparcos satellite (see *Figure 3*). This mission was designed to carry out high-precision astrometry, and photometry using its photon-counting image dissector tube equipped with an S20 photocathode to determine so-called Hp magnitudes. In the event, an average of 110 observations were made of 118,000 programme stars (mainly brighter than V = 10) to a typical internal precision about 0.0015 mag on the Hp median magnitude. Figure 4 depicts the actual distribution of Hipparcos stars across the sky: as you can see, coverage extended across the entire sky making it an ideal photometric catalog.



Figure 3



# Figure 4

During the planning for the mission it was realised that additional two-color photometry could be achieved using the star mapper, which worked in scanning mode, and which yielded the so-called, Vt and Bt magnitudes. Many more stars were observed with Tycho than with Hipparcos and it is because of this that Tycho magnitudes have been adopted by many observers as reference stars. However, the typical precision of Tycho data is only about 0.0120 mag for stars of similar brightness to Hipparcos (V<10), i.e. a factor of eight worse! One would have to measure 50 - 100 times as many Tycho stars to drum down the error in the Tycho median to a value comparable with a single Hipparcos star measurement and that's not taking into account the fewer photons on average per Tycho star. For Tycho stars of magnitude V = 11, the photometric precision is about 0.1 mag, i.e. yet another factor of eight worse than for bright Tycho stars, making them effectively useless as a source of photometric references.

Clearly, it is the Hipparcos Catalog rather than Tycho that has tremendous potential as a source of reference stars for minor planet photometry but how best can it be utilised?

# Some issues and how to tackle them

Any observing methodology based on Hipparcos needs to address three important aspects (*Figure 5*):

# Some issues and how to tackle them

 For CCD photometry, at V = say 7.0 - 9.5 Hipparcos stars are bright, too bright ?
 CCD fields are too small to include Hipparcos stars so conventional differential photometry is not possible ?
 Hipparcos magnitudes are not V magnitudes ?

3. Hipparcos magnitudes are not V magnitudes ? But how do the two systems compare when it comes to asteroids ?

Figure 5

One concerns the fact that the majority of Hipparcos stars lie in the magnitude range, V = 7.0 - 9.5, such that most CCDs will saturate in 1 - 10 seconds at this brightness level using say a 20-centimeter aperture scope?

The second concerns the average separation distance of an asteroid from the nearest Hipparcos star, which is expected to lie in the range 30 - 60 arcminutes, i.e. outside the field of view of most small CCD cameras.

Thirdly, it is essential that instrumental magnitudes can be accurately calibrated against the Hp magnitude system, and that Hp magnitudes can also be accurately transformed to the standard Johnson V magnitude system.

How do we tackle each of these three aspects so as to optimise observing methodologies? Well the first item on the shopping list is a computercontrolled Goto telescope mount for reliably locating each minor planet and reference star on the CCD chip. Using a mount of this type, it is possible to first image the asteroid say using a 30second exposure and then quickly move to a nearby Hipparcos star, which can then also be repeatedly imaged using a much shorter exposure. Finally the sequence can be completed by returning to the asteroid and carrying out another 30-second integration. This entire sequence of images and downloads may take about 2 to 3 minutes but should provide sufficient data from which the V magnitude can be determined to an accuracy of between 0.01 and 0.03 mag. How accurately this can be done depends on the precision with which the hardware is calibrated, details of which I shall describe shortly.

Before I do, I will recommend one further refinement of the telescope hardware, that is to set up a second CCD camera and smaller aperture scope on the same mounting as the main instrument and aligned in the same direction (see for example *Figure 6*). This configuration is chosen to allow simultaneous acquisition of signal from a neighbouring Hipparcos star at the same time that the signal from the asteroid is accumulated even though the asteroid is separated by one degree or more from the star. Two-channel operation of this kind is a powerful way of compensating for shortterm changes in atmospheric transparency and has been widely used with photomultipliers as the detector. Of course to capture one or more Hipparcos stars, it is necessary to select a telescope/CCD camera combination which has sufficient area coverage of the sky. Typically, the second scope should have a focal length of between 150 and 400 millimeters and should be operated at an intermediate f-ratio, say around f/5 to f/10. By this methodology, several short-exposures of the Hipparcos field are taken, then combined, to determine the instrumental magnitude of each

reference star captured. These are then compared with contemporaneous data for the asteroid obtained with the main instrument. To calculate the magnitude of the asteroid in the standard Hipparcos system, one CCD camera has to be cross-calibrated against the other so as to determine their relative gain. This is best carried out at intervals several times during an observing run by pointing to one of the fainter Hipparcos stars nearby (say one in the range, V = 8 to 10) and then taking many short exposures through both instruments, say of 1 second duration or even less so as to avoid approaching saturation of any CCD pixels of the larger instrument. The Hipparcos star selected for the purpose should not be too dissimilar in color to that of the asteroid, i.e. it should have a B-V color in the range +0.6 to +1.0. Taking lots of short exposures in this way is rather akin to amateurs who co-add lots of planetary images to beat atmospheric seeing and should provide a better measure of the relative gain of the two instruments throughout an observing run. It is yet to be seen how stable the relative gain of two CCD cameras operating in the same environment can be but I expect this to be good and in any event its absolute value can be monitored throughout the observing run.



Figure 6

#### Calibration – a key issue

I have now addressed the first two issues outlined above so now let us move on to the key question of calibration against the Hp magnitude system, and the subsequent transformation to the standard Johnson V magnitude system. Here the choice of CCD is very important so that a good match can be achieved between the instrumental system of the CCD and that of Hipparcos. Some CCD cameras have been purposefully designed to have a pseudovisual response, notably those of the SuperHAD type manufactured by Sony. Figure 7 illustrates the response of this type of detector compared with the standard V passband and the effective Hipparcos response as determined by Bessell. The first thing to note is the relatively good fit between the unfiltered SuperHAD response and that of Hipparcos. The second point to note is the equal-area symmetry between Hipparcos and

the V passband indicative of a good match between the two systems even though Hipparcos has a much broader range. When operating in unfiltered mode, the choice of CCD is crucial since most devices are excessively sensitive beyond the red cut-off of the V passband and as such require filtration of the light.



# Figure 7

Given a suitable choice of CCD, the conversion from instrumental magnitude to Hp magnitude can be accurately carried out using an appropriate transformation equation which is derived empirically from the data.

To illustrate this point, I shall show some results of my analysis of CCD images taken by my colleague, Andy Hollis for purposes of calibration. I asked Andy to set up his MX516 CCD camera on an undriven short-focus scope pointing roughly in the direction of the meridian and directed at about declination +20 degrees and to take repeat images every 5 minutes or so for as long as possible. He used an 8-second integration time to avoid trailed images and an effective aperture of only 3.5 centimeters to image an area of sky a little over 3 square arcdegrees in size. His CCD camera is equipped with a Sony ICX083AL chip, which is of the SuperHAD type and has a broadband pseudovisual spectral response, which he used unfiltered.

Several Hipparcos stars were registered on each frame so that it was possible to compare the instrumental magnitudes of each star. The bluest star in the field was selected as the reference and the difference between the measured instrumental magnitude and the Hp magnitude of the other Hipparcos stars was determined. A total of 70 differential measures were made from 31 CCD images for stars brighter than V =8.0. Relatively bright stars were selected to ensure an adequate signal to noise ratio. The value of (v-Hp) was found to depend linearly on the color difference of each pair of stars as shown in *Figure 8*. The slope of the relationship is what we need to know to be

able to transform our measurements from our instrumental system to that of Hipparcos. This slope was found by least-squares linear regression to amount to -0.151 +/- 0.007, i.e. the MX516 CCD is slightly more red-sensitive than the Hipparcos detector. Advantage of using a CCD camera having a spectral response close to that of the Hipparcos detector are that a more linear calibration can be achieved and the dependency on color difference is less marked. A linear calibration is especially useful since any corrections applied when carrying out asteroid photometry need only depend on the *difference* in the color of the asteroid and that of the Hipparcos reference star and not on their absolute values.





How accurately can we transform our instrumental magnitudes to the Hipparcos system? Note that the calibration data shown here were achieved without any flat-fielding of the CCD, so they could be considered to be the worst case. The standard deviation amounts to 0.046 mag on average for a single 8second integration. Ten such 8second integrations with the CCD displaced slightly each time would reduce this uncertainty to about 0.015 mag. With flat-fielding, this value would certainly be lowered to 0.01 mag or even better. As to corrections due to color difference, if we select stars having B-V color indices in the range +0.2 to +1.0, then on average, the asteroid will differ by about 0.3 mag in color compared to the reference star. This corresponds to a color correction of 0.045 mag with an uncertainty of less than 0.003 mag, which together with an uncertainty in the catalog magnitude of the Hipparcos star of less than 0.002 mag means little extra uncertainty in the result is introduced through the process of transforming to Hp magnitudes. Overall, with flatfielding, the error in the derived Hp magnitude of the asteroid is expected to be close to  $\pm 0.01$ mag.

So we now have one final step to consider, that is the transformation of the Hp magnitude of the minor planet to the Johnson V system. To this end, I have analysed photometric data for those Landolt stars that were also measured by Hipparcos. I

found a very high degree of correlation between the two datasets as shown by Figure 9. In the B-V range, -0.3 to +1.0, the scatter on individual points about the best-fit correlation amounts to 0.004 mag. Furthermore, in the range, +0.6 to +1.0, which encompasses the vast majority of asteroids, the correlation is linear and the scatter even less - see Figure 10. In correspondence with Brian Skiff, he pointed me in the direction of a recent paper by Michael Bessell, which included analysis of Hipparcos data for several hundred so-called Eregion standard stars. These stars, which occupy 10 regions of the sky all roughly situated at a declination of 35 degrees South, were measured by Cousins and by Menzies using the same magnitude system as Landolt. As in the case of my own analysis, Bessell derived correlations between differences relative to Hipparcos and color. I therefore compared Bessell's fit for E-region standards with my own for Landolt stars as shown in Figure 11 - the residuals between the two are extraordinarily similar agreeing to within 0.002 mag across the B-V range -0.15 to +1.0. Combining both datasets (Figure 12), we arrive at the following linear transformation for asteroid photometry:

$$V = Hp - 0.087.[B-V] - 0.074$$

which is good at better than the 0.002 mag level for B-V colors in the range, +0.6 to +1.0.



Figure 9



Figure 10



Figure 11



Figure 12

#### Rotation rates and light curves as co-products

Although precision V photometry is the tool by which the nature of magnitude - phase angle relationships are to be determined, it should be selfevident that all measured datapoints will also be subject to rotational modulation. The value of the data will only be properly realised if the entire dataset for each asteroid at any one apparition is

used to construct a coherent rotational lightcurve. For many medium-to-large asteroids the rotation rate is already known so that a simultaneous solution for the magnitude as a function of phase angle and rotational phase should be relatively straightforward. For those objects whose rotation rate is unknown or indeed uncertain, more photometric measurements will be required to arrive at a unique solution for both the rotation and phase angle effects. If V photometry can be performed to say better than 0.02 mag, for an object exhibiting an amplitude of 0.2 mag, something of the order of 15-20 separate observations will be required to solve for the rotation rate and phase angle effects. As such, coordinated observing campaigns by say two or three amateurs at different worldwide locations would be ideal.

From an observational point of view, advantage is to be gained if each V photometric sequence for a particular object is repeated say 30-45 min later. The reason for this is that paired observations allow one to determine the rate of change of brightness of the object not only from absolute photometry as just described but also from differential photometry relative to appropriate field stars in the same CCD frame as the asteroid. Accurately quantifying whether the asteroid is getting brighter, getting fainter or merely standing still in brightness facilitates the construction of a unique rotational lightcurve. Using paired observations of this kind, I expect that some 10-12 separate observing runs might be sufficient to yield a unique solution for each object monitored in this way.

Given the approach I have just outlined, by spending two 5-minute observing intervals per asteroid per night, a total observing time of as short as 120 minutes might be sufficient to not only quantify phase angle effects but also to solve for rotation rate and lightcurve in the bargain - the key to the prize is high-precision V photometry. So there you have it!

# Conclusions

I hope that the messages are clear:

1. For Vband asteroid photometry, the reference catalog of first choice should be Hipparcos selected to meet the criteria: 5.0 < V < 9.5 and +0.2 < (B-V) < +1.0

2. Using CCD cameras having a 'pseudovisual' response such as the Sony SuperHAD type, it is possible to perform accurate absolute photometry working in unfiltered mode provided Hipparcos stars are used as references

3. An observing methodology is recommended whereby a second CCD camera attached to a coaligned shorter focal length, smaller aperture telescope or lens, is used to take simultaneous images covering an area of sky of a couple of square degrees and capturing Hipparcos stars in the process

4. I envisage an observing project with plenty of scope for amateurs to contribute, and which is aimed at accurately quantifying the nature of the magnitude - phase angle relationships of the various asteroid classes, with particular emphasis on extending observations to as small a phase angle as possible. Rotation rates and lightcurves are also generated in the bargain.

My case rests. Now over to you folks!

Richard Miles rmiles@baa.u-net.com

# CLOSE APPROACHES OF VERY SMALL NEAR EARTH OBJECTS AND THEIR POSSIBLE DETECTION IN THE EARTH- MOON VICINITY

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In this paper not a very well known population of very small Near Earth Objects is discussed. We estimate the frequency of the approaches within the Moon distance for 100 m size objects to 1-10 times and for 10 m size objects 2400-24 000 times per year. We also propose an outline of a new survey system. This optical system would discover up to 20 - 200 objects per year.

Key words: close approach, NEO, telescope system

#### Introduction

More than 208 000 minor planets with more or less precise orbits are known at present. Only 2105 of them are Near Earth Objects (November 2002) with perihelion distances smaller than 1.3 AU. Discoveries of new NEOs are influenced by strong observational selection effects. We are limited by sensitivity of telescopes, rapid angular velocity in the sky, almost no concentration towards ecliptic that is why new NEOs can be found in the entire sky. But current discovery programs cannot cover the whole sky during a single night. This paper is focused on the population of very small NEOs, smaller than 100 meters in diameter and their possible discoveries in the close vicinity of the Earth. This size of NEOs is also very dangerous for life on the Earth and their collisions with the Earth are much more frequent than collisions with 1 km size asteroids.

The first goal of this work is to figure out the probability of 100 m to 10 m Very Small Near Earth Asteroids (VSNEAs) encounters with the Earth within the mean Earth-Moon (0.0026 AU) distance. The second goal is to suggest the parameters for the equipment suitable for discovery program of such small asteroids in the vicinity of the Earth. The distance 0.0026 AU is not selected by chance for the close encounters. The idea is that the Earth-Moon distance is our close vicinity and VSNEOs have visual magnitude brighter than 14 in this distance in suitable geometrical conditions. The 14th magnitude is a limit for small telescopes.

Δ	Date	Name	H (1, 0)	Reference
(AU)			(mag)	
0.0007 *	1994 Dec. 9.8	1994 XM1	28.0	MPEC 1994-
				X05
0.00080	2002 June 14 1	2002 MN	23.4	MPEC 2002-
0.00000	2002 June 1 1.1	2002 1111	20.1	M14
0.0010	1993 May 20.9	1993 KA2	29.0	IAUC 5817
0.0011	1004 Mar. 15 7	1004 ES1	28.5	MPEC 1994-
0.0011	1994 Mai. 13.7	1994 ESI	20.5	E05
0.0011	1991 Jan. 18.7	1991 BA	28.5	IAUC 5172
0 00205**	2001 Jan 15 0	2001	25.8	MPEC 2001-
0.00203**	2001 Jan. 13.9	BA16	23.0	B35

Table 1. Observed close approaches. D - the geocentric distance in AU, Date of close approach, H(l, 0) - the absolute magnitude. \* - this approach is to within 112 000 km, \*\* - closest approach to the Moon was at 0.00053 AU on 2001 Jan. 15.80 TT

The main NEO discovery programs (e.g. LINEAR, Spacewatch, LONEOS, NEAT) are focused on minor planets greater than 1km in diameter. Their strategy is to discover such asteroids in greater distances from the Earth and reach 21st visual limiting magnitude instead of larger field of view. That is why they cover the whole sky within one lunation (approx. 20 days). The celestial objects with rapid angular velocity are almost impossible to be discovered by this type of telescopes. Discovery of such a close object is only a chance process. Until now, we know only 6 NEOs of this type, which were discovered and followed up. They approached the Earth closer than the distance of the Moon. Most of these objects were discovered at distances about twice as 0.0026 AU.

Small objects are observed only a few hours during close approach to the Earth. They change brightness, angular motion and phase angle very quickly. As an example we can use for demonstration a recently discovered (June 17, 2002) object 2002 MN at a distance of 0.018 AU with the absolute magnitude of 23.6, which corresponds to the diameter about 100 m. Its minimum distance to the Earth was 0.0008 AU (120000 km) on June.14.09, 2002. It changed the phase angle from 150° to 60° and the magnitude from 21 to 10.7 during several hours in the time of approach. Its maximum motion in the sky was 1000 arcsec/min. The asteroid was discovered 3 days after the closest approach to the Earth due to its rapid angular motion in the sky. No current telescope system was able to discover this object during the closest approach though it reached 10.7 visual magnitude.

Close approaches of asteroids larger than 100 m are not very frequent. As we show, smaller objects with the size about 10 m to 100 m approach the Earth within the distance of the Moon several thousand times per year. However, these smaller objects are a possible hazard for the Earth. An object with the diameter about 70 m produced the Tunguska event. According to Ceplecha (1996), this range of sizes is responsible for almost half of the total influx of interplanetary bodies onto the Earth.



Figure 1. The number of all known NEOs (Nov. 2002) with the given absolute magnitude (a). The cumulative number of all known NEOs as a function of the absolute magnitude (b).

## The known population of very small objects

The albedo for most NEAs is not known. That is why we do not know most of their diameters. We suppose that visual albedo of asteroids range from 5 to 25 percent. Then asteroids with the absolute magnitude H (1, 0) = 23.5 have the diameter 50-120 m and those with H (1, 0) = 28.5 have the diameter 5-12 m. We will assume that a 100 m asteroid has H(1, 0) = 23.5 mago and a 10 m asteroid has H(1, 0) = 28.5 in this paper.

The whole population of NEOs greater than 1 km is assumed to amount to  $1000 \pm 200$  which depends on different authors (Rabinowitz et al. 1994, Bottke et al. 2000, Galád 2001, Morrison et al. 2002, etc.). However, we know orbits of about 60 percent of this size NEOs. The population of small NEOs (< 100 m) is almost unknown. NEOs with diameter 100 m and smaller represent 13.6 % of the whole known population and smaller objects than 10 m represent only 0.6 %. This is demonstrated in Figure 1. The left graph shows the number of NEOs vs. the absolute magnitude and the right graph shows the cumulative number versus the absolute magnitude. The peak in numbers is near the 19 magnitude for objects with a slightly smaller diameter than 1 km. The observed number of smaller objects decreases very quickly instead of growing as was suggested by Rabinowitz et al. (1994) for real population.

The IAU Minor Planet Center published on its web pages (IAU MPC 2002) a list of close approaches calculated from year 1900 until 2178. The results are showed in *Figure 2*.



Figure 2. The number of calculated close approaches in 1900-2178 (IAU MPC, 2002) for all known NEOs within 0.1 AU (a), The number of calculated close approaches for all known NEOs within 0.1 AU and brighter than magnitude 14 (b). The number of calculated close approaches for all known NEOs within 0.01 AU (e). The number of calculated close approaches for all known NEOs within 0.01 AU and brighter than magnitude 14 (d). The brightness is calculated for model phase angle 60°.

Figures 2a,b show close approaches within 0.1 AU. Figures 2c,d show close approaches within 0.01 AU. The number of close approaches grows in the last years (Fig. 2a,c), which is due to better asteroid surveys sky coverage. These objects, which we observe as close approaches in these years, did not come close to the Earth in the past 100 years and also will not come close to the Earth in the next about 100 years. A strong selection effect is evident, which prefers asteroids in closer geocentric distances. And also it means that we know only a small part of the real population, from which the flux of objects comes close to the Earth constantly.

Precise ephemerides for the time of close approaches are beyond the aim of this paper, we set a model phase angle  $Ph = 60^{\circ}$ .

*Figure 2b* shows the number of approaches within 0.1 AU in particular year and only those which are brighter than magnitude 14 (Ph =  $60^{\circ}$ ). The number of such approaches is distributed almost uniformly from 1900 until 2178. Just the recent years provide a small peak in bright approaches. We can conclude that most of the bright objects within 0.1 AU are asteroids with greater diameter.

Table 2. Calculated close approaches of known asteroids within 0.0026 AU from 1900 until 2178. 6. - the geocentric distance in (AU), H(I,O) - the absolute magnitude, mag - the visual magnitude for phase angle 60°.

Name	Date	6	H (1, 0)	mag
2002 FD6	1911 Apr. 6	0.0025	22.2	11.3
2002 CU11	1925 Aug. 31	0.0023	18.3	7.3
2001 BA16	2001 Jan. 15	0.0020	25.8	14.5

2002 MN	2002 June 14	0.0008	23.6	10.3
1999 AN10	2027 Aug. 7	0.0026	17.8	7.0
2000 SB45	2037 Oct. 8	0.0014	24.3	12.2
2001 WN5	2039 June 27	0.0014	18.2	6.1
2000 SG344	2069 May 1	0.0006	24.7	10.7
2001 BA16	2081 Jan. 15	0.0021	25.8	14.6
2000 WO107	2140 Dec. 2	0.0005	19.1	4.7
1998 OX4	2148 Jan. 22	0.0020	20.7	9.4
1998 KY26	2167 June 12	0.0010	25.4	12.6
2000 LG6	2170 May 26	0.0021	29.1	17.9

Closer approaches within 0.01 AU and brightness greater than magnitude 14 are very rare during a particular year as is showed in *Figure 2d*. The result is that we almost do not know the population of such close approaches due to the observation selection effect mentioned above.

The last column of *Table 2* shows the apparent magnitude in the time of the close approach with the model phase angle of asteroids  $Ph = 60^{\circ}$ . It is clear from these values that at the time of close approach their magnitude is mostly below 14 also with the phase angle, which is not very favourable.

There are 13 objects (*Table 2*), which come within 0.0026 AU from the Earth in 1900-2178. Ten of them are brighter than magnitude 14 with  $Ph = 60^{\circ}$ . For illustration there are 20 objects, which come within 0.003 AU and 13 of them are brighter than magnitude 14. Similarly, there are 134 objects within 0.01 AU and 68 of them are brighter than magnitude 14.

The above mentioned values are changed very quickly because the orbits are recalculated with new observations and also newer close objects were



discovered in the last years as it is shown in *Figures* 2a,c.

Figure 3. The estimate of NEOs greater than the given diameter (a) (Rabinowitz et al. 1994). Collision frequency of NEOs with the Earth (b) (Morrison et al. 1994). Collision frequency as a function of diameter and mass of object according to different authors (e) (Rabinowitz 1993).

# **Estimates of the approaches**

According to Rabinowitz et al. (1994) the estimated number of the whole population of NEOs greater than 100 m is 135 000 with uncertainty by factor 2 and die number of objects greater than 10 m is  $1.5 \times 10^8$  with uncertainty by factor 4 (*Figure 3a*).

Also the ,great uncertainty is in the estimates of NEOs collision rate with the Earth. We observe just a fraction of impacting bodies and mostly without any direct physical properties as a diameter, specific mass, impact velocity and so on.

These parameters are calculated from indirect observations of electromagnetic waves, shock waves, seismic waves etc. The collision frequency of 100 m size objects with the Earth is about 1 object per 1000 years and 10 m size 1-10 times per year according to Ceplecha 1992), Rabinowitz et al. (1994) and Morisson et al. (1994) and this is shown in *Figure 3b,c*. The uncertainty is about one order m the case of small 10 m size objects. There is sorne evidence that 10 m size objects are probably of a cometary origin and are about 10 times more populated as the same size asteroids Ce lecha 1992).

If we extrapolate the Earth as a target for impactors with the radius R = 6378 km into the target with the radius of the Moon mean distance 384 400 km then we can in the first approximation estimate the number of objects virtually hitting such an extrapolated target. Then according to the collision frequency with the Earth we can estimate the virtual collision frequency within the Moon distance. There are about 1-10 100 m size objects and 3600-36 000 10 m size objects per year. But we have to take into account the Earth's gravitational attraction which increases the number of impacts. Then the efficient cross-section of the Earth will be about 1.5 times larger. This means that the estimated number of 10 m size approaches within the Moon distance per year has to be decreased by about 1/3 to 2400 -24 000. Again the uncertainly is great in these estimates because we do not know exact number of impacts, but on the other hand, we can obtain a preliminary image of how often such objects approach to the Earth. It would be interesting to compare these estimates with direct observations.

# Possible discovery of small NEOs during their close approaches to the Earth

#### Angular velocity

As it was mentioned in the introduction section, a rapid angular motion at close approaches almost disables their discoveries for the current telescope systems. We calculated the geocentric velocity for all known NEOs, orbits of which are closer to the orbit of the Earth than 0.1 AU (704 objects). The

resulting mean geocentric velocity is 15.66 km/s. We have chosen two model geocentric velocities 28.5 and 6.5 km/s as typical maximum (95% of objects have lower velocities) and typical minimal geocentric velocities (95% of objects have greater velocities), respectively. If the object moves tangentially with respect to the observer with the geocentric velocity 28.5 km/s and 6.5 km/s then its angular velocity will be 15.3 '/min and 3.8 '/min, respectively, in the distance of the Moon. *Figure 4a* shows the angular velocity as a function of the geocentric distance  $\Delta$ . The rapid angular velocity is the main reason for disability of detection of close approaches, especially for the telescopes with a small field of view.



Figure 4. The angular velocity of close approach (a) as a function of the geocentric distance D(AU) for model tangential geocentric velocities  $(V_{gt})$  28.5 km/s and 6.5 km/s. The brightness as a function of the geocentric distance D(AU) for model absolute magnitudes 23.5 and 28,5 (b).

## <u>Magnitudes</u>

*Figure 4b* explains how close approaches change brightness of asteroids with the geocentric distance. We assume the phase angle  $Ph = 0^{\circ}$  for two model objects with the absolute magnitude H(1, 0) = 23.5mag and H(l, 0) = 28.5 mag, which represent 100m and 10m size objects, respectively, with low albedos (about 5%). We also assume that majority of objects will reach in some time during a close approach (phase angle change rapidly due to small distance to the observer) a phase angle close to Ph = 0°. Then about 100m size object would be brighter then 10 magnitude and about 10 m size object would be brighter then 15 magnitude in the distance of the Moon. Otherwise we have to take into account their lower brightness due to worst geometric condition of the phase angle. However, the 10m object would reach magnitude 14 in a half distance of the Moon, then the number of objects will decrease to 1/4 of the earlier estimated population in the previous section.

# <u>Specific region with higher probability of new</u> <u>discoveries</u>

The brightness near opposition is the highest and also the phase angle is the smallest. This condition is the most suitable for new discoveries. The phase angle is the same as the angle from opposition in the case of very close approaches e.g. within 0.0026 AU. That is why the higher probability of new discoveries is near opposition in spite of the fact that close approaches have no concentration on the sphere. If we set the phase angle less than about Ph ~  $(60^{\circ} - 70^{\circ})$ , then the selected region with a given phase angle will cover 1/3 of the whole celestial sphere, which is about 14  $000^{\circ^2}$ .

# The outline of the survey system

We propose the basic characteristics of the survey system for detection of close approaches of very small NEOs for Modra Observatory and for other sites in the world with different amount of the observation time. This system should cover significant amount of the whole sphere during a single observation night up to the limiting magnitude of 14.

We need to set the minimum field of view of the proposed system and we have to take into account the following limitations:

- the average observational night lasts for about 5 hours (based on the data for the Observatory Modra in Central Europe);

- each star field has to be exposed at least twice for identification of a moving object;

the assumed exposure time is about 1 minute, longer exposure will not be effective due to a rapid angular motion of the object on the celestial sphere;
the system should cover minimum 1/3 of the sphere during a single night of observation.

From these conditions, we derive the minimum field of view of the survey system, which is about  $100^{\circ^2}$ . This field of view with the limiting magnitude of 14 during 1 minute exposure is the basic parameter of the system. Of course, it is necessary to think about effective exposure time due to the rapid angular motion of the object. To reach the effective exposure time about 1 minute for an object with the typical angular velocity (see *Figure 4a*), it is clear that we have to design extraordinary parameters of the survey system as a focal length and size of detector element.

# <u>Probability of detection with the proposed</u> <u>system</u>

The approach frequency of 100 m size objects is low (1-10 per year), we estimate the probability of detection or discovery frequency per year from the population of 10 m size objects.

Our estimation of detections comes from the following items, if we assume randomly distributed close approaches during the year and on the whole sphere without any specific concentration:

- the average number of hours during the year is about 850 (based on the data for the Observatory Modra), which is about 1/10 of the year (day and night);

- the system would cover 1/3 of the whole sphere during the night;

- the limiting magnitude 14 decreases the number of 10 m close approaches to 1/4 of the earlier

estimated number in the previous section.

Then, if we take interval 2400 - 24000 close approaches within 0.0026 AU during the year, which means 1 close approach per hour on average, we can estimate up to 20 - 200 detections per year with this system.

But we have to think about not very suitable geometric conditions during approach and, moreover, the close approaches within 0.0026 AU last just a few hours or a day. The probability of detection decreases with the angular motion of the object due to reduction of the effective exposition on a single element of the detector. The estimation of how all these effects will influence the detection needs to develop a dynamic model of orbits of close approaches. We plan to develop such a dynamic model in the future work. All these factors decrease the number of detections. It implies that the proposed system would detect less than 20-200 objects per year.

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# **153P/IKEYA-ZHANG AND THE COMET OF HEVELIUS**

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The apparition of 153P/Ikeya-Zhang = C/2002 C1 (Ikeya-Zhang) has been one of the most important cometary apparitions of recent years. For the first time a comet with a period greater than 156 years has been observed at more than one apparition. Despite the identification of C/1661 C1 with 153P/Ikeya-Zhang there remains the questions of the inferred major change in the light curve between 1661 and 2002 and of the original preferred identification with C/1532 R1, which has a strikingly similar orbit. One possibility is that C/1532 R1 and 153P are fragments of a single object that split in the past. A possible splitting scenario is examined. The possible identifications are correct, the absolute magnitude of the comet has faded considerably with time, although this in itself may be consistent with an object that is evolving photometrically after a major splitting.

#### Introduction

Comet C/2002 C1 (Ikeya-Zhang) is the first confirmed return of a comet with a period greater than 155 years (the previous record holder was Comet Herschel-Rigollet, last seen in 1939). Suntoro Nakano suggested initially that the comet might be identical to C/1532 R1 but, as more data became available, he showed that C/1661 C1 offered an even better linkage. This linkage was later accepted as definitive, although attempts to link to previous returns of the comet have been inconclusive, although strongly suggestive.

Although C/1532 R1 was observed from September 2nd to December 30th. C/1661 C1 was less well observed. It was discovered on 1661 Feb. 3 in the dawn sky, just after passing perihelion, with a tail already 6° long. The comet faded rapidly and was last seen on March 28th. The orbit used for the former in the IAU/CBAT/MPC "Catalogue of Cometary Orbits" is that of Olbers, calculated in 1787. The orbit is not completely determined, despite the long visibility of the comet and a 1785 solution by Méchain gave a rather different solution, with an inclination of 42°, and an Ascending Node of 126°. For C/1661 C1 the orbit used is the one calculated in 1785 by Pierre Méchain. These orbits are compared below to that of Comet Ikeya-Zhang. As we can see, the similarity with the Olbers orbit of C/1532 R1 is quite impressive. The similarity with C/1661 C1 is less so; its longitude of perihelion is very close to the corresponding value for Ikeya-Zhang, although other parameters are not quite so close.

	C/2002 C1	C/1532	C/1661
	(Ikeya-Zhang)	R1	C1
Т	2002 Mar.	1532 Oct.	1661 Jan.
	18.9388	18.832	27.381
q	0.507200	0.51922	0.442722

Z+	0.017337		
	34°.5777	24°.53	33°.450
	93°.4156	93°.81	86°.562
e	0.991207	1.0	1.0
i	28°.1110	32°.59	33°.015

On seeing this similarity, the overwhelming impression is that the three objects may all be related and that both C/1532 R1 and C/1661 C1 may be fragments of a single object that split in the past. The possibility of a connection between the comets of 1532 and 1661 seems first to have been appreciated by Halley, in his "A Synopsis of the Astronomy of Comets" of 1705, who suggested that they were in fact one and the same comet. But what then of the initially favoured identification of 153P/Ikeya-Zhang with C/1532 R1? Could the comet of 1532 and the 1661-2002 comet be fragments that split from each other in the distant past? The similarity of the orbital elements seems to suggest so. Based on Nakano's Feb 25 1661-2002 linked solution, the previous calculations indicated that the apparition prior to 1661 occurred in 1273 April/May. Given that a comet is recorded in the Chinese annals as being first sighted on 1273 April 9, it is reasonable to ask whether this is in fact another record of Ikeya-Zhang or merely a coincidence. What leads us to the former opinion is that the details given of the comet's apparent motion mimic rather well the expected track of Ikeya-Zhang if its perihelion passage were about a month earlier than that indicated by the preliminary calculations.

The comet of 1273 was first seen by the Chinese at the ecliptic longitudes of the Hyades and to the 'north' of Auriga. This latter is rather imprecise but still useful for our purposes. Of more use is the statement that the comet subsequently passed from the asterism  $28/\nu/\phi/0.15$  UMa and then penetrated the 'ladle' of the Plough. This piece of information effectively limits an Ikeya-Zhang type orbit to

having a perihelion passage time between March 26.5 and 28.5. The record then goes on to say that the comet passed through Bootes and reached the region of  $\pi$  Boo. All of this happened, according to Ho's translation, in 21 days. For our orbit this track would be covered in two months and the end point would be nearer to  $\eta$  Boo. To a certain extent, such details are negotiable (due to possible copying errors etc.) but the time period is something of a problem, as is the visibility for the extended period if the comet were indeed Ikeya-Zhang with its current absolute magnitude.

In spite of the possible identification problems we now assume that the comet of 1273 was indeed Ikeya-Zhang and see how it can help us in our quest to reconcile C/1532 R1 with Ikeya-Zhang. We take as starting point the MPEC 2002-F55 orbit solution and then introduce non-gravitational terms into the integration to move the previous perihelion time from mid-1662 to 1661 Jan 28.900. This can be achieved by any number of possible pairings of the non-gravitational parameters A1 and A2, as shown in the table below which gives sample sequences of perihelion passage times derived by integration from the 2002 epoch.

A1 =	0.626925	0.60723	0
A2 =	0	-0.0062435	-0.198742
	1661 Jan.	1661 Jan.	1661 Jan.
	28.90	28.90	28.90
	1273 Apr.	1273 Mar.	1270 Sept.
	26.2	27.7	24.8
	879 Jan. 5	877 Aug. 7	798 May 3
	426 Nov. 3	451 Oct. 22	314 Mar. 2
	-61 July 16	-59 Nov. 8	-155 Feb. 25

By including nongravitational effects in his 1661-2002 linked solution Nakano (April 15) initially found A1 = 1.76 and A2 = -0.0129, leading to perihelion passages of 1661 Jan 29, 1273 Feb 23, 877 July 7 and 452 Oct 23. A recent revision of this by Nakano (April 26) gives A1 = 1.64 and A2 = -0.0163 - resulting in a sequence of previous perihelia of 1661 Jan 29, 1273 Feb 7, 877 Feb 23, and 458 July 31.

Although there are many possible comb inations of A1 and A2 that will give the desired result as regards 1661, if we want to force a fit to our possible 1273 comet at the same time then the options become rather limited. For instance, if we were to want to fit to, say, T = 1273 Mar. 30 then the orbit prior to 454 would have been hyperbolic due to a close (0.12au) approach to Jupiter. However, a close approach to Jupiter in the 5th Century would be an attractive scenario for causing a splitting of the nucleus. Given that the window of solution for the 1273-1661-2002 linkage is very limited around 450 due to the position of Jupiter, it seems reasonable to assume

that the splitting occurred around this time in order to take advantage of the Jovian perturbations about 400 days after perihelion passage. Also, if we assume that the splitting actually occurred at perihelion then the difference in the assumed nongravitational effects will have separated the two fragments by enough to produce useful differential Jovian perturbations when the fragments pass through their descending nodes. As we will see though, other scenarios are perfectly possible too.

Less attention has been paid to linkage by Nakano to 877 despite the fact that this was his initial linkage to the 1661-2002 observations, which then permitted linkage between 877, 1661 and 2002.

The Japanese record a Guest Star in Pegasus that appeared on February 11th (Ho 307). A comet was also observed in the west from Europe for 15 days in March and a comet in China in June & July (Pingré 349). However, a "Guest Star" (ko-hsing) was usually a nova, especially if no movement was recorded. In oriental chronicles a comet was a "huihsing" if tailed and a "po-hsing" if not, thus there must be considerable doubt about the suggestion that the object was a comet.

Nakano links the Japanese and European observations with 153P, although he uses only a single position for the Guest Star in Pegasus. Support for the comet interpretation though can be garnered from the fact that Pegasus is at sufficiently high galactic latitude to make a nova unlikely, if certainly not impossible. Yeomans states that the European comet was seen in Libra, in the southwest in the morning sky. Nakano's linkage puts the comet in eastern Cygnus, in the eastern sky at dawn! Theoretically it was just visible at magnitude 3 at this time in the north-west at sunset from northern Europe, but very low in a very bright sky. It looks very unlikely that it would have been observed in the evening sky, but would have been easy at dawn.

Thus, while the linkage with the comet seen in 1273 looks highly plausible, there are real difficulties with the linkage to 877 and it is far from certain that the objects recorded by Ho and by Pingré are one and the same.

## Clues in the light curve

C/1532 R1 was evidently an exceptional object. David Hughes's 1987 catalogue of cometary absolute magnitudes from 568 - 1978 assigns it an absolute magnitude of +1.8, one of just 12 comets that has an absolute magnitude of +2 or brighter, putting it into the "giant comet" class, almost 100 times intrinsically brighter than the average long-period comet. In contrast, C/1661 C1 is a more normal object. David Hughes lists its absolute magnitude as +4.6, much closer to that of Ikeya-

Zhang, particularly as the observations suggest that the comet became diffuse and faded out rapidly. The light curve fit to C/2002 C1 (Ikeya-Zhang) from the observations in the archive of The Astronomer magazine (provided by courtesy of Guy Hurst) – below – suggests an absolute magnitude of 7.2, slightly fainter than average for a "new" comet.



This leads to an immediate problem: 153P/Ikeya-Zhang was very much fainter intrinsically than either C/1532 R1 or C/1661 C1. The 1661 light curve mystery is an important part of the problem of linkage. A look at the observational circumstances for 153P/Ikeya-Zhang in 1660/61 shows that, of the four returns that are treated here this was the most favourable. The comet was bright and had excellent pre-perihelion visibility, yet neither Hevelius, nor any other observer recorded it in the evening sky.

Date	Comet	$m_1$	Sun	Moon
31/12/1660	14°	+3.0	-17°	New
05/01/1661	15°	+2.6	-16°	Crescent
20/01/1661	12°	+0.7	-14°	Waning
23/01/1661	9°	+0.4	-13°	Last Quarter

Hevelius would have had two chances to discover the comet pre-perihelion in the evening sky if it was as bright as we believe:

- 1. In late December-early January around New Moon at magnitude 2.5-3 in a dark sky.
- 2. After the January 15th Full Moon around magnitude +0.5 in twilight.

Even if the comet had been missed in late December when it would have been low in the west after sunset in a practically dark sky, with a magnitude around +3, the comet would have been very bright and extremely obvious low in the twilight, after the end of nautical twilight (i.e. with only the horizon lit) after the January full moon. Even assuming widespread bad weather, if the comet was as bright as thought it would have been seen by someone before perihelion and would have been bright enough to be widely observed by the general public.

John Bortle (Bortle, J.: 2002, TA, 38, 455, 298) argues convincingly that the best solution for the apparent discrepancy between the brightness of the 1661 and the 2002 returns of Comet Ikeya-Zhang may be a strong perihelion asymmetry in the light curve of the comet. Such an asymmetry would have important dynamical implications for the comet's orbit too and would significantly affect extrapolations of the orbit into the past. Even if we invoke the enduring photometric effects of a splitting event at a previous perihelion passage that would gradually diminish with time and could account for the comet having a significantly brighter absolute magnitude at a previous return.

However, the observed light curve shows that the degree of perihelion asymmetry at the 2002 return was very small.. The main conclusions of the study of the extensive *The Astronomer* data archive are that:

- 1. There is only a very slight perihelion asymmetry amounting to no more than 0.2 magnitudes.
- 2. Peak brightness was attained approximately 2 days after perihelion.
- 3. The peak brightness of the innermost coma as measured by CCD photometry in a 10 arcsecond aperture was reached approximately a week before perihelion.

The complete TA archive up to the end of March



with the fit to the light curve derived from the sample of data used in the April TA is shown left. Although not perfect, the fit obviously gives a good approximation to the light curve.



The peak brightness of the comet was approximately magnitude 3.5 in the days just after perihelion. However, as the geocentric distance was decreasing at that time, the date of peak apparent brightness and that of the true peak brightness are not the same. To correct for this we subtract 5\*log  $\Delta$  from the apparent magnitudes to shift them to a standard geocentric distance of 1AU. This plot is shown here. The dispersion in the plot is around 0.8 magnitudes, but it does appear that the true peak brightness is shifted very slightly to the right of the axis (i.e. post-perihelion). The effect is 2±1 days.

This shows that there was no large perihelion asymmetry in the light curve. It also implies that the simplest form of the non-gravitational terms, as expressed in Graeme's accompanying article, may be a good approximation to the true situation in C/2002 C1 (Ikeya-Zhang), although he notes that even a very small perihelion asymmetry can have important dynamical implications (an order of magnitude estimate is that a 1 day asymmetry in the non-gravitational term leads to a 3 month change in the perihelion date at the last return.



Note that the TA database confirms that the comet has been significantly brighter post-perihelion than pre-perihelion. The fit to the light curve (above) shows that the best fit to the data has a brightening rate that is very similar, but with the post-perihelion data systematically 0.4 magnitudes brighter. Some caution must be applied to the rate of fade postperihelion as the brightening event observed in the light curve in late April significantly flattens the

apparent rate of fade. When these data are ignored the rate of brightening pre-perihelion is indistinguishable from the rate of fade postperihelion. The comet is found to have shown a 0.5 magnitude brightening in late April that continued for some 3 weeks. At the peak of this event the comet was actually brightening in real terms as the heliocentric distance increased.

Investigation of the data shows that the small perihelion asymmetry in the date of maximum brightness may be due to the phase angle term. In other words, shadowing of dust grains in the coma. The plot below was prepared as a test from on-line ICQ data that was made to assess the possible size of the effects of perihelion asymmetry on the nongravitational terms. The residuals from the best light curve fit are shown. Note that in the top plot there is a significant trend to brighter magnitudes post-perihelion. When a phase angle term is included the residuals flatten out although two interesting effects are seen. Note that the comet brightens quite significantly from mid-April. There is also a *possible* sinusoid in the residuals that has been noted in other data sets. This shows the characteristic signature expected from a precession of the nucleus with a period of approximately 6 weeks. However, to confirm this feature will require a very much longer data set probably at least double the one shown here.



It is of interest to note that recent data shows that the morphological behaviour of the comet has reproduced an effect seen in Hevelius's comet of 1661. As commented in the March TA, Hevelius's comet became very large and diffuse and faded out rapidly. This effect was present in C/2002 C1 (Ikeya-Zhang). Visual observations in May 2002 showed that the coma was half a degree or more

across and extremely diffuse, with DC=0-1 such that became difficult to observe despite remaining a relatively bright object. The coma diameter estimates give a consistent linear diameter of 250 000km around perigee in late April, but that by June  $10^{\text{th}}$  the coma measured 1.3-1.5 million kilometres in diameter.

The brightening event in late April 2002 is interesting. It could be interpreted as a perihelion asymmetry, although it is too little too late to explain Hevelius's observations in 1661 (and his lack of observations pre-perihelion). If we fix "n" and allow "H<sub>0</sub>" to vary we obtain the following curve:



We see that  $H_0$  brightens from 7.07 at perihelion, to approximately 5.4, but this brightening starts at around T+35d, far too late to explain the presumed light curve in 1660/61. This brightening is also of too small amplitude to explain the lack of visibility in late January 1661, even if it were to have initiated much earlier relative to perihelion.

The light curve suggests that there are problems with the identification of a comet seen by the Japanese and Koreans as being the same as the Chinese comet.

Ho's comet catalogue lists a broom star seen by the Japanese (Feb. 5) in the evening sky and the Koreans (Feb. 17) in the morning sky.

As we have seen, the Chinese saw a "bluish white guest star with the appearance of loose cotton" (a classical description of a tailless comet) in Auriga on Apr. 9th.

– Ho lists the two as identical (Ho 439), although their position and movement seems incompatible with this.

- Nakano links the former with 153P/Ikeya-Zhang (T = 1273 Feb. 4.8) based on the evening-morning shift.

This suggests that there may be a transcription error in the date(s) of observation of the Japanese/Korean comet, as there was in the 4BC "Star of Bethlehem" event.

If we assume that the comets of 877, 1273 and 1661 had the same light curve as the observed light curve of 153P/Ikeya-Zhang in 2002, we find that the

problem of visibility and compatibility with the observed dates of observation becomes progressively worse.



We see that, for example, in the Waddington linkage to the 1273 apparition, we see that the comet would, given the 2002 light curve, barely pass magnitude +4 and in 877 would only reach 3.5, whereas it is evident that at both returns the comet was much brighter than that. Both Nakano and Waddington's linkage suggest that the comet would have been barely naked eye visible when observed by the Chinese in the evening sky. However, the Chinese observation of colour in the comet suggests that it was very bright. If the Waddington linkage is correct the comet would have been magnitude 1.5 and fading at discovery, even if it was as bright as Hevelius's comet in 1661 and thus too faint to show colour!! We must assume then that it was even brighter in 1273 than in 1661.

This suggests that there has been a systematic fade of the comet since at least 1273, which is consistent with post-splitting activity.

What if C/1532 R1 and 153P/Ikeya-Zhang are fragments of a single comet that split in the 1st Century AD? The very bright (m0= 1.8) comet of 1532 would be the principal nucleus. The descending node of 153P is close to Jupiter's orbit and permits very close encounters. A post-split encounter with Jupiter could separate the nuclei allowing returns of the fragments in 1532 and 1661. There are many possible scenarios, but one would have a splitting during an apparition in 58AD, followed by an encounter with Jupiter in 458AD that separated the fragments in T.

# Conclusions

Although the 1661-2002 linkage is firm, there are major problems with the linkages to 1273 and to 877, although the evidence of a linkage to the Chinese comet of 1277 is strongly suggestive. The evidence suggests that the comet has faded significantly over its last 3 apparitions. This is consistent with 153P/Ikeya-Zhang being the smaller fragment of a comet that split early in the first millennium AD. Comet C/1532 R1 would be the

principal nucleus of the split comet. If this scenario is correct we can expect this nucleus to return in the late 21<sup>st</sup> Century.

<u>Author's Note:</u> This text is based on a series of articles published in The Astronomer magazine by

Mark Kidger and Graham Waddington between March and June 2002. The author is grateful to Graham Waddington for many long and fruitful discussions and for his collaboration in the articles in The Astronomer.

# THE NUCLEUS OF NON-PERIODIC COMETS:

Measure of the diameter of the nucleus of inactive comets of large period

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One of the most important topics in cometary physics is the size of the nucleus given that the nucleus is the driver of cometary activity. At present knowledge of the nucleus size and albedo is mainly limited to evolved periodic comets. A knowledge of the properties of a sample of new and relatively new comets is important. Since 2002 a new generation of telescopes and infrared instrumentation brings the possibility of applying the same infrared flux method used to measure the diameters of asteroids to the determination of comet nucleus diameters and with it the possibility of making accurate determinations of the equivalent diameter and albedo for a large sample of comets.

# Introduction

To date most measurements of the diameter and, from it, the albedo and active fraction of comets have been made by indirect means. Only for three comets have good diameters been measured: 1P/Halley the Giotto (from spacecraft); 19P/Borrelly (from Deep Space 1); and 81P/Wild 2 (from Stardust). These direct observations have shown that the characteristic equivalent radius and albedo for evolved comets is in the range from 1-5km, with albedos typically from 2-4%, even lower than had been estimated from groundbased observations.

Estimates of the diameter of the nucleus have been made both from the minimum brightness of the (presumably) inactive nucleus (the method pioneered by Tancredi et al.), or by PSF fitting from HST images (Lamy et al.). The results for the two methods agree reasonably well for the few objects in common to the two data sets. In general though, the radius derived from the brightness of the inactive nucleus is probably only accurate to a factor of  $\pm 2$  in most cases, thus leading to a probable error of a factor of 4 in active area and related parameters. Little though is known of the sizes and albedos of new and relatively new objects. Are they members of the same population of properties as highly evolved Jupiter-family comets? Or do they have generally higher albedos and larger active fractions?

## The problem of cometary nucleus measurement

An illustration of the problems involved with the measurement of cometary radii is seen in C/1995 O1 (Hale-Bopp), surely the most studied comet in history. Many estimates of the radius have been made using a wide assortment of techniques (eg:

Fernandez, Y.: 2000, EM&P, 79, 3; Sekanina, Z.: 2000, EM&P, 77, 147). The results have given a huge range of values from  $\approx$ 12-65km, implying 2 orders of magnitude of uncertainty in the volume and mass of the nucleus. The main uncertainty is caused by the coma and its contamination of the signal from the nucleus. This problem can be resolved though if we can apply the infrared flux method to the bare nucleus of the comet.

The infrared method, jointly with occultations, has led to accurate measures of the equivalent diameter and albedo for many asteroids, allowing families to be identified and global properties of the asteroids to be studied in detail. The method depends on combining visible and thermal infrared data. As the visible brightness of an asteroid or nucleus depends on both its albedo and its radius with just a single known (the visible brightness) we can only calculate the product of albedo and equivalent radius. However, in the thermal radiation reradiated in the infrared is inversely proportional to the Bond albedo "A", i.e., it depends on 1-A. Thus, if the visible and thermal infrared fluxes are known, we can solve directly for the albedo and thus for the radius.

The difficulty with the infrared method is that it must be applied to a completely inactive nucleus to avoid coma contamination. Similarly, as the distance at which a comet becomes inactive increases, the Wien displacement law shifts the peak infrared emission further into the midinfrared, as well as reducing the peak intensity. This has led to the problem that the mid-infrared instrumentation that has been available has lacked the necessary sensitivity to detect the weak emission from the distant and cold nucleus.

# The new generation of infrared instrumentation

As ground-based infrared observations are background limited, the limiting flux for a telescope scales as the diameter of the telescope to the 4<sup>th</sup> power. This means that for a relatively small increase in telescope diameter, the sensitivity gain is very large. Between the 3-m NASA Infrared Telescope Facility (IRTF) in Hawaii and a 10-m telescope the gain in sensitivity is more than a factor of 100. This means that measurement of the thermal radiation from ground-based telescopes has become feasible.

In recent years a whole series of 8-10 metre class telescopes have become available to the astronomical community (e.g. Keck I and II, Gemini North and South, Sabaru, and the VLT), with all offering recently commissioned midinfrared instrumentation of plan to have such instrumentation available in the near future. At the same time, the Spitzer Space Telescope (previously SIRTF) known as will permit sensitive measurements of objects from space. For the first time it will be possible to calculate the equivalent radius and albedo of a significant sample

# CanariCam – an opportunity for Spanish planetary scientists

Spanish scientists have to date been excluded from the possibility of cutting-edge solar system work in the mid-infrared due to lack of access to suitable telescopes and instrumentation. This situation will change in 2005-2006 with the entry in service of the 11.4-m Gran Telescopio CANARIAS (GTC), which will have the state of the art mid-infrared multi-mode instrument "CanariCam" as a Day 1 instrument.

CanariCam is a huge advance on previous instruments. Compared to ISO, the GTC+ CanariCam combination offers a telescope diameter a factor of 17 greater (10-m equivalent aperture, against 0.60-m), giving a corresponding increase in spatial resolution (0".18 @ 8µm compared to 3" for ISO). The increase in collecting area also means that the sensitivity of CanariCam will be similar to or better than ISO (CanariCam will have a  $k\sigma/1hr$ limiting flux of 40µJy, compared to 50µJy limiting flux for the faintest objects extracted from ISO images). CanariCam will also have better spectral resolution (R≈1400, compared to R≈1000 for ISO), plus polarimetric and coronagraphic modes that were not available on ISO.

# The interest of measuring the parameters of the nucleus

At the time of writing, there are direct measurements of the radius of the nucleus and albedo for just 3 comets, all highly evolved Jupiter family objects, and all observed in spacecraft encounters. Indirect measures have been made of the nucleus diameter for 5 more objects using profile fitting from high-resolution HST images. Apart from these, 105 periodic comets have had their nucleus radius, albedo and active fraction estimated from the brightness of the (presumed) inactive nucleus close to aphelion. These last have a probable uncertainty of a factor of 2.

The measurements made to date suggest that there is a minimum radius for cometary nuclei of  $\approx$ 1km. It has been suggested that this may be a physical property of cometary nuclei – i.e. that smaller objects are unstable or of very short lifetime – but it is also possible that the 1km limit may represent a selection effect due to the faintness and lack of activity of such small nuclei.

Similarly, there is considerable interest in the comparison of global properties between evolved and new objects. In particular, is the albedo as low for new objects as it is for Jupiter family members (typically taken to be 4%), especially given that the albedo of the increasing number of trans-Neptunian objects that have been measured is closer to 10%? The relationship between the size distribution for new and highly evolved Jupiter family members will also give important insights into the long-term evolution of comets. So far though there are no accurate determinations of the size of any non-periodic object.

However, most short period comets have some residual activity even at aphelion. Some comets (e.g. 2P/Encke, 10P/Tempel 2) even show a brighter nucleus absolute magnitude at aphelion than at smaller heliocentric distance. For the infrared flux method to work we must deal with totally inactive cometary nuclei. This generally means observing comets that satisfy one of the following criteria:

- Comets with P>20 years and thus aphelion at r>>5AU (e.g. 1P/Halley, 109P/Swift-Tuttle, 153P/Ikeya-Zhang).
- Comets with very low activity at moderate r (e.g. many "LINEAR" comets).
- Large comets that are active at large r, but that can be detected in the mid-IR at very large r (e.g. C/1995 O1 (Hale-Bopp).

These criteria though imply observing objects that are faint and thus difficult or impossible to detect with ground-based 3-4 metre telescopes.

The high sensitivity of the GTC+CanariCam combination means that many objects will be easily

detecable. The estimated thermal infrared flux of the nucleus of C/1995 O1 (Hale-Bopp) is 0.9mJy @ r =17AU – it's distance in 2003. This is easily measurable with CanariCam on the GTC. A good detection (5 $\sigma$ ) can be made in only 100s of integration.

We estimate that nuclei a third of the diameter of the nucleus of Comet Hale-Bopp could be detected at the same heliocentric distance in 10 000s of integration. Even smaller nuclei can be measured if they deactivate at smaller heliocentric distances.

Ironically though, the sustained activity of C/1995 O1 (Hale-Bopp), which still exhibits an active coma at r>19.5AU, means that definitive measurement of the diameter of the nucleus may have to be delayed several more years.

# Conclusions

The advent of new large telescopes with state of the art instrumentation means that our knowledge of the global properties of cometary nuclei are going to increase exponentially in the next few years. However, the random arrival of new comets in the inner solar system means that these objects will be targets of opportunity as their date and heliocentric distance of deactivation will not be predictable in advance. The first detections of bare nuclei in the mid-IR are likely to be made by Sptizer during 2004 and it is to be hoped that a significant sample of objects will be detected and equivalent radii and Bond albedos measured within the next 5 years allowing the properties of periodic and non-periodic comets to be compared directly for the first time. We expect CanariCam and the GTC to play a major part in this study.

# AMATEUR CCD PHOTOMETRY OF COMETS: HOW TO STANDARDISE DATA

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A difficulty that observers face when taking data of comets is how to standardise their data to make it compatible with other observers using different instruments. The widespread use by amateurs of CCD cameras of high sensitivity and good cosmetic quality enormously increases the possibilities of photometric coverage of comets given that photometry is calculated automatically with astrometric observations. Although the MPC database now contains huge amounts of comet photometry, the lack of any standard method for taking this data means that the dispersion in photometry of a comet in the MPC database may be as large as 2 magnitudes at a given date even for magnitudes given as "N". In this paper we explore a standard system of photometry that is widely used by Spanish and Italian observers based on the USNO A2.0 catalogue and a series of standard photometric apertures. The suitability of the USNO catalogue for photometric work is examined critically and examples of comet light curves and coma profiles are shown. A transformation of USNO A2.0 to the standard Landolt BVR system is presented.

#### Introduction

Possibly the biggest revolution in cometary astronomy in the last 50 years has been the recent widespread use of CCDs by amateurs to take large quantities of high-precision astrometry of comets. In the last five years the use of CCD cameras with a sensitivity and cosmetic quality as high as those of the professional CCDs of the 1990s has led to a huge explosion in the amount of astrometry that has become available, both of comets and of asteroids. Amateur observers are regularly obtaining highquality astrometry of objects down to magnitude 20, allowing precise orbit determination to be made within a few nights of the discovery of a new object. This revolution is reflected in the increasing size of the MPC database and also in the explosion in the number of site codes that have been asigned. Most astrometric packages that are widely used, both by amateurs and professionals, such as Astrometrica, provide not only an accurate position for a comet or asteroid, but also calculate an estimated magnitude. Thus the explosion in astrometry of comets has also led to a huge explosion in the amount of CCD photometry available. Unfortunately. potentially this photometry is difficult to understand and even more difficult to use as it is obtained with a mishmash of apertures, methods and bandpasses. This leads to the potentially fabulous resource of the amateur cometary CCD photometry archive being massively underutilised.

#### The problem

Amateur CCD photometry is potentially an even more important resource for cometary research than astrometry however, to make it usable we have to find some way of standardising it. Any system that is adopted must obey three rules: 1. Don't make it too complicated. If you do nobody will use the method.

This has happened with the ICQ format for CCD photometry which was so complicated and anti-intuitive that many astronomers complained that it stopped them submitting their data.

2. Amateurs have limited time and resources. Adapt the method to what they can do.

We must accept that an amateur astronomer works in his or her spare time and does not have the capability to spend many hours on adapting data. Any system must be rapidly and easily usable and should not require them to buy additional expensive equipment.

3. Don't be too demanding. Accept a reasonable compromise on quality.

Any system will be a compromise between the quantity and the quality of the data that is obtained. It makes no sense to put in place a system that decreases the amount of acceptable data by a large factor for only a small gain in quality. Similarly, the data quality that is obtained must be high enough for the data to be usable in research.

We must also work within some restrictions that, while possibly not to our taste, are facts of life that must be accepted:

- Most amateurs do not have either standard astronomical filters, or a significant fraction of photometric nights. It is no good demanding that they use standard stars or a standard photometric system!
- Comets are usually not point sources: they have their own special problems when we take photometry of them. This means adapting the photometric routines to take photometry in a different way to asteroids.

In other words:

 Common sense says that we will just have to accept unfiltered observations and relative photometry against field stars. This has been a standard astronomical technique for many years.

• We have to make the best of what we have.

# The basic "Spanish method"

CCD observers in Spain have been using a standard system of photometry of comets for several years. This system has been evolving with time to maximise its utility and efficiency. Data taken with this system has now been used in several photometric studies published in professional journals. A comparison of amateur results using this technique and dedicated professional photometry shows minimal differences in the values of Afr that are obtained (Kidger, 2004, A&A 420, 389, "Dust production and coma morphology of 67P/Churyumov-Gerasimenko during the 2002/2003 apparition II. A comparative study of production 46P/Wirtanen dust in and 67P/Churyumov-Gerasimenko during their 2002/2003 apparition").

The steps involved are

- 1. Assume that an unfiltered CCD observation approximates to the photometric "R" band (usually a good assumption).
- 2. Recommend reducing with Astrometrica which has a good, robust photometric method and gives a reliable estimate of the error.
- 3. Take a standard aperture for the photometry.
  - Spanish observers use 10".
  - This is a sensible compromise between pixel size and seeing, as against measurement errors.
- 4. Calibrate using USNO A2.0 "R" magnitudes.

More recently, a dedicated reduction routine prepared by Julio Castellano (MPC site code 939) has been prepared by a Spanish observer (FOCAS) that allows data to be obtained in multiple apertures (10, 20, 30, 40 and 60", although for very large comas 150 and 300" may be used). One important aspect of FOCAS is the fact that it uses the median of the entire frame for sky background determination, rather than taking an annulus around the photometric aperture that causes coma to be subtracted from coma in extended objects.

However, given that most observers have urban sites with high levels of light pollution, with the background as high as magnitude 15 per square arcsecond, photometry becomes increasing unreliable due to sky subtraction errors for larger apertures, particularly with fainter comets. This often means that the best and most reliable photometry is obtained with the 10" aperture as the amount of sky background within the aperture is only a quarter of that in the 20" aperture.

# The USNO catalogue and its reliability

Some astronomers criticise the use of USNO magnitudes for any photometric application, not specifically photometry of comets, alleging that it is not a photometric catalogue and that it is unreliable. Two recent USNO products are available: USNO A2.0, obtained from scanning POSS-I plates from the 1950s; and USNO B1.0, obtained from combining various surveys such as POSS-I, POSS-II and the AAO SERC southern survey. There is also a recent CCD catalogue, the UCAC, although with a brighter limiting magnitude

It should be stressed that the USNO catalogues are not intended to be photometric catalogues, nor are they designed to give precise photometry, although considerable effort has gone into their photometric calibration which, at the bright end, is tied in to high-precision photometry Tycho stars. However, provided that the limitations of the USNO catalogues are known and understood, they are usable for photometric applications.

Why use USNO A2.0? There are four basic reasons:

- It is widely available.
- There are many USNO stars in the field of view of the average comet. It covers a very wide range of magnitudes to much fainter than the limiting magnitude of any amateur CCD.
- It is by far the best of the USNO products in the R band (superior in accuracy to UCAC)
- There isn't anything better at present!

We have tested USNO A2.0 photometry against the IAC catalogue of high precision photometry of AGN fields in the Landolt system. This catalogue presents 22 000 observations over 75 nights in BVRI of 437 stars in 26 AGN fields, with a median accuracy  $\approx 0.01$  mags (see: Kidger et al.: 2004, New Astr. Rev., 48, 505, "A resource for multifrequency campaigns: a revised catalogue of UBVRIJHK calibration stars in AGN/blazar fields" for a description of the catalogue). The photometry was used to check the magnitudes in B, V, and R USNO obtained from photometry, where Astrometrica approximates the V magnitude from B and R as V=(3\*B+5\*R)/8.

The results are shown below where the USNO magnitude is plotted against the IAC photometry for B, V and R. The diagonal line is the line of photometric equivalence, where USNO "R" would be equivalent to the standard R. Note that in R the points are distributed around the line of equivalence, showing that the USNO A2.0 R magnitude is very close to the standard R. In

contrast, USNO A2.0 B magnitudes are systematically too bright at the faint end of the magnitude scale, with an error of 0.8 magnitudes at B=19.

In the following two plots, the detailed fits for B and R are shown.



USNO "B" is systematically too bright for stars fainter than B=13. An USNO B=19.2 corresponds to a true magnitude of B=20.



USNO "R" is very close to the Landolt/IAC "R" magnitude. At R=11, USNO is about 0.2 magnitudes too faint and at R=18 about 0.2 mags too bright. This though is within the margin of error on an observation. The USNO A2.0 photometry is, in this respect, far superior to USNO B1.0, for which the transformation to the standard R magnitude is much larger.

Although the USNO catalogue is not a photometric catalogue, the errors in its photometry are greatly exaggerated by non-users. Below we show the histogram of the measured errors on the magnitudes of stars.



Note that a few stars do have extremely large errors. However, after correcting for the transformation from USNO A2.0 R to the standard R, the median error on the magnitude is 0.197 magnitudes – i.e. 50% of all stars are this accurate, or better. This is also far superior to both USNO B1.0 and UCAC. The standard deviation of star magnitudes is 0.246 magnitudes (i.e. 67% of all stars have an error of this size or smaller). Such errors are comparable with the errors to be expected on CCD photometry of extended objects. Note that both Astrometrica and FOCAS clip stars that give highly discrepant photometry – these are not used in the magnitude determination.

If we look at the distribution of errors on USNO A2.0 R magnitudes, we find both good and bad news. The fraction of stars with accurate photometry is commendably high, a small proportion of stars though have extremely large errors, although a significant fraction of these may be variables.

Error	Fraction	
<0.05 mags	16.9%	
<0.15 mags	39.4%	
<0.25 mags	59.3%	
>0.5 mags	11.0%	
>1 mag	1.0%	

If we use USNO photometry sensibly then, it is a valuable resource for comet and asteroid observers.

- NEVER calibrate against single stars.
  - Many programs, such as Astrometrica and FOCAS, calibrate against all stars in the field.
  - ✓ Astrometrica and FOCAS eliminate the stars that give discrepant photometry.
  - ✓ As a first approximation the uncertainty in the magnitude reduces as the square root of the number of stars used.
- The biggest issue for observers is sky subtraction, not the accuracy of star magnitudes.

# Results

The typical error on a CCD observation is found to be approximately 0.2 magnitudes. The biggest source of dispersion is observers who fail to apply the standardised method correctly, with the most common problem that of incorrect sky subtraction, although some CCDs also have a sensitivity that more closely approximates to Johnson V than to R.

An example of results is shown below for C/2002 T7 (LINEAR) which shows the power of this method. The first plot shows the raw light curve from data submitted the taken to "Observadores\_cometas" mailing list (Observadores cometas@vahoogroups.com). Data are split into estimates of the total visual magnitude - dark blue rhombuses - CCD photometry with a 10" aperture – pink squares – and CCD photometry with other apertures – brown circles. Note that there are some outliers, although this are consistently due to the same few observers.

There is a disadvantage with the fixed aperture method and that is that as the geocentric distance changes we are using a variable physical aperture size, thus the amount of coma that enters in the aperture is varying. Two approaches to this problem are possible.

The simplest approach is to convert the photometry to an aperture-insensitive photometric measure. The best and most widely used one is the equivalent column of dust Afp in centimetres defined by A'Hearn et al. (1984, AJ, 97, 579). The conversion of the CCD photometry for all apertures to Afp is shown in the following plot. Note two large outbursts at r=2.7 and r=6AU, corresponding to 2003 December and February respectively. At perihelion, Afp  $\approx$  20 000-cm, corresponding to a peak dust production of approximately 0.7 Halley.





We can use the relationship defined by Osip et al. (1992, Icarus, 98, 115) to covert Afp to the dust production rate. The result is shown below. Peak dust production is approximately 3 tonnes/s, compared with a peak water production of approximately 18 tonnes/s.



If the water content of the gases of C/2002 T7 (LINEAR) is the same as that for 1P/Halley -71% by mass – the peak gas production rate at perihelion for the comet was 25 tonnes/s (approximately 0.15 Halley) and the gas to dust ratio is approximately 8, implying that C/2002 T7 (LINEAR) is an unusually dusty comet, despite being dynamically new. This gas to dust ratio should be compared to the value of 4.8 for the exceptionally dusty C/1995 O1 (Hale-Bopp). However, at the peak of the outburst in December 2003, the gas to dust ratio was as low as 2.

The inconvenience of the fixed aperture size is that using a single aperture gives no information about the coma profile apart from having a variable physical size with  $\ddot{A}$ . Some Italian observers use fixed physical sizes of aperture, but it is difficult to find appropriate sizes for comets that have a large range of  $\ddot{A}$  as the size of aperture that is appropriate for a comet at, say, r=7AU, becomes totally unmanageable when the comet approaches the Earth to 0.5AU. FOCAS allows photometry to be calculated in several apertures for a single measurement. This allows coma profile information to be obtained. You can then use the measured profile to calculate the magnitude in any aperture and to unify CCD data with visual estimates, or to calculate photometry for a fixed physical aperture from any data set. However, in most cases we expect the coma to obey an  $r^{-1}$  law thus, if we define the coma index as:

## $R = \log a + b \log r$

Where "R" is the magnitude in R with an aperture of diameter "r" arcseconds, we expect to find that the coma index "b" = -2.5, which is the result that is obtained in the majority of cases.



But for C/2002 V1 (NEAT) this approach did not seem to work. The extrapolated CCD magnitudes were totally inconsistent with the observed total visual magnitude estimates.

On investigation it was found that a two-component fit to the coma was required, with an extended coma that followed a different brightness distribution. For objects with such a large coma as C/2002 V1 (NEAT) larger apertures (150 and 300") were required to define the coma brightness distribution. Note that a similar result was obtained over a wide range of magnitudes and thus heliocentric distances during the apparition (see below).

How reliable are the results obtained by the photometric method described here? A comparison of the values of Afp obtained from dedicated professional photometry of 46P/Wirtanen using narrow-band filters to isolate continuum emission, taken during the 1997 return in support of the ROSETTA mission (open circles) and unfiltered amateur photometry taken during the 2002 return (filled squares) is shown in the final plot. Note that the agreement is excellent.

We thus conclude that the method described here really can generate photometry of a good enough quality to be used in professional research.





## Conclusions

- With sensible rules one can obtain very consistent CCD photometry of comets even with unfiltered cameras and USNO A2.0.
- Custom programs such as FASE3 and its successor, FOCAS, written by Spanish amateur Julio Castellano and now widely distributed permit easy astrometry and multiaperture photometry.
  - It has a good sky subtraction and photometry algorithm adapted to real amateur data.
- This allows coma profile and evolution information to be obtained with minimal effort.

The results for 46P/Wirtanen show that even unfiltered amateur photometry can produce data on dust production rates of a quality comparable to dedicated professional photometry in narrow band filters if this method of taking photometry is carefully applied.