Astron. Astrophys. 348, 1035–1039 (1999)

ASTRONOMY AND ASTROPHYSICS

Search for Trans-Neptunian objects: an automated technique applied to images obtained with the UH 8k CCD Mosaic Camera

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Received 20 July 1998 / Accepted 14 October 1998

Abstract. In this paper we present the results obtained with a new program dedicated to the automatic detection of trans-Neptunian objects (TNOs) with standard sets of images obtained in a same field of view. This program is available freely from the World Wide Web server of the Observatory of Besançon (http://www.obs-besancon.fr/www/publi/philippe/tno.html) and is designed to be used with the Munich Image Data Analysis System (MIDAS) developped by The European Southern Observatory (ESO). It has been tested with observational data collected with the UH 8k CCD mosaic Camera on October 27, 1997, at the prime focus of the CFH telescope (Mauna Kea, Hawaii). These observational data had lead, by the classical method of blinking, to a first detection of a new TNO with a magnitude estimated at 23.6 and an unusually high orbital inclination (i≃33°). The program managed to detect this object, as well as detecting another TNO (m_R ≃23.9), confirming its ability to detect faint moving objects.

Key words: methods: data analysis – techniques: image processing – solar system: formation

1. Introduction

Since the first discovery of a Trans-Neptunian object (TNO) a few years ago (Jewitt & Luu 1993), the search for other similar objects has involved more and more observers and telescopes. Nowadays about 60 TNOs are officialy registered by the IAU and one can expect many other discoveries in the near future. This observational effort involves more and more astronomical data that need data processing in order to identify, usually near the sky background noise, the very faint TNOs.

The usual procedure used to detect new TNOs has been described by Jewitt & Luu (1988). It consists in obtaining several images of a same field of view, separated by about 1 or 2 hours (3 images is the minimum). These images are examined in order to detect all the moving objects and to measure their velocity, which is the main criterion used to classify the objects as TNOs or asteroids. Indeed Kepler's third law shows that the apparent velocity (expressed, for instance, in arcsecond/hr) of an object like a TNO (with an orbit supposed nearly circular) is directly related to its heliocentric distance. For an object observed near opposition, as it is usually done, we have: $v(arcsec/hr) = 148\{\frac{1-R^{-0.5}}{R-1}\}$, R being the heliocentric distance of the observed TNO (expressed in AU).

For a typical value R=40 AU one obtains $v = 3.2$ arcsec/hr. Indeed, with three or four images obtained with an integration time of about 15 mn and separated by about two hours, a TNO appears as a point-like object in different places separated by a few arcseconds. Thus the detection criteria for TNOs is different than that for asteroids; the main difference being that in a single image a TNO appears as a point-like object rather than as a streak.

So far several authors have published results obtained with automatic detection procedures. First, Levison & Duncan (1990) described the results obtained with a search program dedicated to TNOs. This program did not manage to detect any TNOs, but the authors mention the use of their own program that is based on an object-list algorithm. More recently Irwin et al. (1995) were the first to detect TNOs with an automated algorithm. This algorithm was also especially designed for the search for TNOs, but used a different method (creation of difference maps, assuming that the seeing does not vary too much for the different images). Also, Trujillo & Jewitt (1998) described an automatic algorithm, similar to the one described by Levison & Duncan (1990), which was used to process some data obtained with the UH 8k CCD mosaic Camera.

In this paper we describe a new program especially optimized for the search of new TNOs with a "standard" set of images. This program has the key advantage, when compared to the works mentioned above, of being designed to be used with one of the main astronomical data processing packages (MIDAS). This feature greatly facilitates the processing of new images.

2. Method used by the program to detect new TNOs

The main criteria used by the program to detect new TNOs are the same as those described by Jewitt & Luu (1988) and used

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with a manual blinking method: (a) the detected objects must exhibit linear and constant velocity motion among the different images, (b) the image shape of the object must be consistent with a point-like object (i.e. with the seeing), (c) the brightness of the object must be constant among images and (d) the rate of motion must be in agreement with a TNO (i.e. less than about 4 arcsec/hr).

In order to limit the number of false detections, we have added to these criteria apparent motion constraints with respect to the ecliptic plane, chosen by the user. The user specifies two limit angles to compare with a vector direction, the purpose being to eliminate "impossible" motions. A test is also performed with the seeing value in order to check if the lack of detection in a single image can be attributed to poor seeing conditions.

As the purpose of the program is to be as automatic as possible, the following steps are used to detect the TNOs from a set of at least three images of a same field of view:

(i) An analysis of each image is performed in using the tools available from MIDAS in order to detect all the objects appearing in each image and to estimate their size and brightness. The key parameter to this analysis is the threshold of detection, which is available as a free parameter for the user. The results are stored in special files.

(ii) From the list of objects obtained with step (i), some of them that can be considered as false detections (i.e. mainly cosmic rays or bad pixels) are eliminated from the files in order to reduce the number of false TNO detections. The criterion used to eliminate these detections is their size: all the objects detected corresponding to single bright pixels are eliminated.

(iii) From the results obtained with steps (i) and (ii), the coordinates (in pixels) of each image are registered against the first image. Note that the images taken of the same field are usually not exactly centered at the same place both because of the accuracy of the telescope pointing system and because it is advisable, in order to make the flat-field, to slightly move the telescope between each image.

(iv) The seeing is estimated for each image and an image having the best seeing is selected. Within this image some objects are classified as "candidate TNOs" because of their small size and brightness. Indeed their size does not exceed the radius of a point-like object (criterion (b) mentioned above) and their central brightness (averaged over the 9 central pixels) does not exceed 100 times the threshold of detection. These two criteria limit to about 4 or 5 magnitudes the magnitude range corresponding to the search for new TNOs (i.e. typically 20 to 24–25).

(v) The other images are then searched for the equivalent objects as shown in Fig. 1. The key parameters, available as free parameters for the user, are: (i) the angles α_1 and α_2, relative to a vector direction (this vector represents the ecliptic plane oriented in the retrograde direction), α_1 and α_2 can be, typically, about -10° to +10°, covering all the possible apparent motions of the TNOs, and (ii) the interval of velocity motion (expressed in arcsec/hr) with 2 to 4 considered typically as acceptable. Of course, the scale of the image (expressed in arcsec/pixel) is a parameter needed by the program. From an object detected in the image having the best seeing another object is searched first in the following image and, eventually, in the other images (see Fig. 1). This procedure corresponds to the criteria (a) and (d) mentioned above.

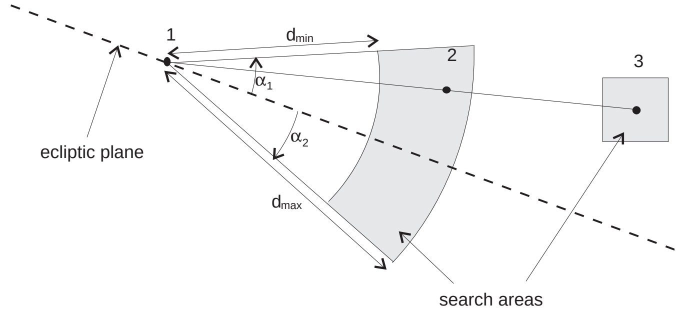

Fig. 1. Schematic view of how the apparent motion of a "candidate TNO" is tested by the program. For an object detected in a first image (position 1) a dashed area appearing around point 2 corresponds to the area where one could expect the object 1 to be located if it has moved like a TNO. Angles α_1 and α_2 are defined by the user and can be typically +10° and -10°. d_{min} and d_{max}, expressed in pixels, are computed by using the acceptable velocity range and the time elapsed between the images 1 and 2. If an object is found in the area 2 its motion is extrapolated and another object is searched in the area 3. This area is a simple square of 10 pixels size centered in the inferred position.

(vi) If an object satisfying the above-mentioned conditions is detected in at least three images another test is performed concerning its brightness: the average difference between the central brightness appearing in the different images and the mean of these values should not exceed 40% of this last value (criterion (c) mentioned above).

(vii) Finally if all these tests have been successful two possibilities can be examined. The first case consists in a good detection in all the images available. In this case the detection is considered secure and the "alarm" is triggered. The second case consists of missing detections in one or several images. In this case the seeing is examined and, if it is degraded by more than 30% (compared to the best one) in the images where the detection is missing, an "alarm" can also be triggered.

Finally, the program announces the possible detections, giving for each object its position in the different images. It is possible to visually check the detection by displaying a unique and composite frame consisting of the area around the object for all the images. The program can be used with images that have only been flat-fielded and bias-subtracted. Nevertheless, completely processed and calibrated images are, of course, preferable.

3. Observational data collected with the UH 8k CCD Mosaic Camera

An observing program was conducted with the 3.60 m CFH telescope, located in Hawaii, using its prime focus and the UH 8k CCD Mosaic Camera. One and a half nights had been allocated, on October 25^{th} and 26^{th}, 1997. These observations permitted to observe three different fields in using the "standard" method (i.e. observations near opposition), during the second night.

For each of these fields eight images, corresponding to the eight CCD composing the UH 8k CCD mosaic camera, had to be processed separately. Each original image had 4096×2048 pixels. Table 1 summarizes the coordinates of the field centers. These coordinates were chosen to avoid the already known TNOs, to be as close as possible to the ecliptic, and to encompass an area as empty of stars as possible. For each field the size was 29′×29′, corresponding to the whole area covered by the UH 8k CCD Mosaic.

These data were processed, taking into account the relatively bad seeing that occured during the observations (from 0.8″ to 1.6″) and the large field of the CCD Mosaic camera. The bad seeing permitted us to bin two by two the images (one pixel covering, then, 0.4×0.4″), greatly decreasing the amount of data to process. After binning each image, the data processing was as follows: (i) Subtraction of the BIAS, using the overscan area of each CCD and through a close fit with a polynomial in the y-axis; (ii) subtraction of the darks; (iii) division by the corresponding flat-field for each CCD and (iv) absolute calibration in units of ph/m^2/s/μm using standard stars.

The flat-fields were a combination of those obtained inside the dome with a tungsten lamp (small scale sensitivity variations) and on the sky (large scale sensitivity variations). With flat A designating the average dome flat, flat B the same flat but smoothed (with a square of 21×21 pixels), and flat C the flat obtained in using scientific frames, then: flat-field = (flat A / flat B) × flat C. This method allows a good correction both for the small scale variations of sensitivity of the pixels and for the large scale variations.

4. Test of the program with artificial faint moving objects

Before using the program on the observational data some tests were performed with artificial faint moving objects. These artifical faint moving objects were added to the images corresponding to the CCD 1 of the field number 3. They were obtained by using the image of a selected star found in each image ($m_R \simeq$ 20) and normalized to different magnitudes before inserting it at known positions corresponding to a velocity motion of 3 arcsec/hr. The following magnitude were used: 21.0, 22.0, 23.0, 23.6, 23.8, 24.0, 24.2, 24.4, 24.6, 24.8 and 25.0.

In testing the program the key parameter appeared to be the threshold of detection. This can be expressed by comparison with the standard deviation of the background intensity due to the sky background noise. For a threshold equal to this standard deviation, the limiting magnitude appeared to be surprisingly high. Indeed all the artificial objects up to magnitude 24.8 were successfuly detected. Nevertheless the data processing appeared to be long and, above all, it appeared that it was nearly impossible to check visually the detections on the computer screen (because of the faintness of the objects). Given that several false detections also occured, such a threshold of detection did not appear practically useful.

Table 1. Fields observed by using the "standard method" with the UH 8k CCD Mosaic Camera. They were obtained near opposition, with 5 images each obtained on October 27th with 15 mn of integration time and a red filter.

Number	R.A.(2000)	Dec(2000)
1	01h35mn00s	+10°00′
2	01h38mn00s	+10°10′
3	01h41mn00s	+10°20′

Table 2. Positions of the TNO 1 detected during the observations conducted the 27th of October 1997 (field 3). Its magnitude was estimated at 23.6±0.3.

UT Times	R.A.(2000)	Dec(2000)
06h14mn	01h41mn11.55s	+10°19′17.9″
07h40mn	01h41mn11.24s	+10°19′15.7″
08h56mn	01h41mn10.96s	+10°19′13.5″
10h20mn	01h41mn10.65s	+10°19′11.2″

Table 3. Positions of the TNO 2 detected during the observations conducted the 27th of October 1997 (field 1). Its magnitude was estimated at 23.9±0.3.

UT Times	R.A.(2000)	Dec(2000)
05h22mn	01h34mn25.41s	+09°55′56.3″
06h48mn	01h34mn25.19s	+09°55′54.8″
08h05mn	01h34mn24.94s	+09°55′53.7″
09h30mn	01h34mn24.69s	+09°55′52.2″

Finally, after different tests, a good value for the threshold of detection appeared to be about 1.5 times the standard deviation due to the sky background noise. The limiting magnitude ($\simeq 100\%$ detection limit) appeared to be about 24.2 on the set of images used for the tests and the time of calculation became more acceptable[1]. Since the mosaic camera consists of eight different CCD arrays, each of them having a slightly different quantum efficiency, the average limiting magnitude can vary slightly around 24.2 depending upon the CCD considered. Nevertheless the examination of the sky level in the different images shows that the difference of sensibilities are very limited, i.e. the variation in the limiting magnitude does not exceed about 0.2 magnitude for a given CCD.

5. Results obtained from the analysis of the observational data

A first examination of the observational data was conducted in November 1997 in order to detect as soon as possible potential TNOs. Using the standard method of blinking, each image was examined carefully and visually on a computer screen. This first examination lead to a successful detection of a TNO appearing clearly in the field 3. This object was apparent on four of the

[1] For a single set of 5 images of 1024×2048 pixels, the calculations take about 15mn with a Digital Alphastation 500, the seeing values beeing given by the user.

Table 4. Orbital elements that can be assumed from the data given in Tables 2 and 3. These elements assume that the TNO 1 (Table 2) is a 2:3 Neptune librator at perihelion. For the TNO 2 a circular orbit (e=0) have been assumed. Seen the very limited set of observations used to compute these elements they should be regarded as relatively uncertain.

Object	Epoch	M (deg)	Arg. lat.(deg)	ω (deg)	Node (deg)	i (deg)	e	a (AU)
TNO 1	1997 Oct. 19	359.9		180.3	207.1	32.9	0.08	39.7
TNO 2	1997 Oct. 19		2.0		23.7	2.1	0	46.7

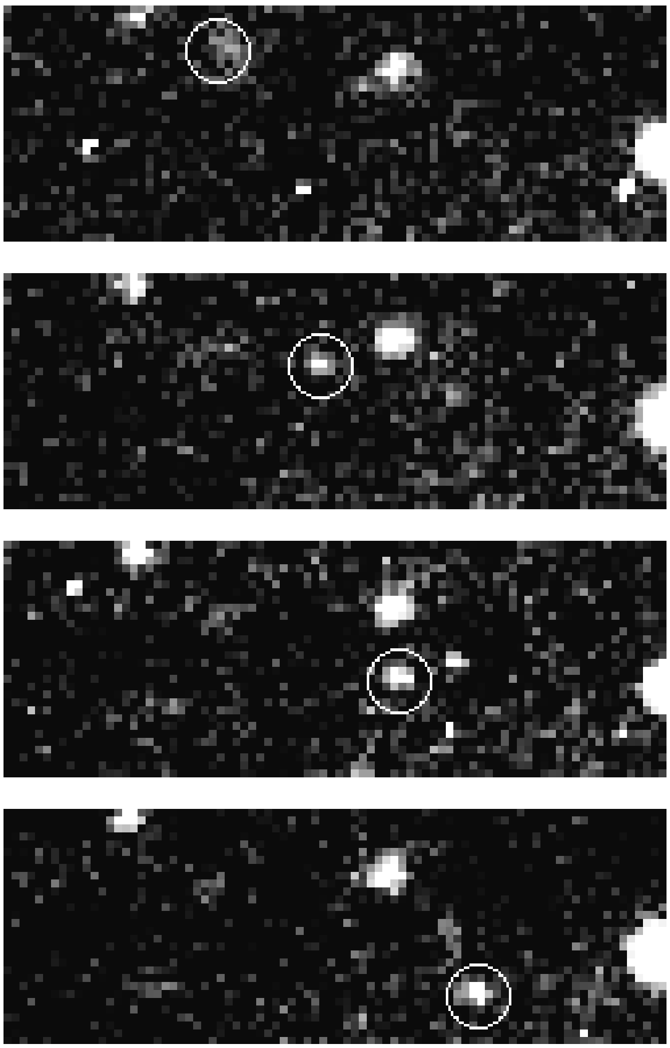

Fig. 2. Details of the images showing the TNO 1 detected on October 27^{th}, 1997 (see Table 2). In each frame the circle shows its position.

five images in the set, the seeing being too degraded on the last one (about 1.6 arcsec). Unfortunatly, this object could not be re-observed by another observer mainly because of its faintness (magnitude 23.6) and, consequently was not officially registered by the IAU. It is now considered lost, because of the very limited time that occurred between the first and last observation.

The positions of the object detected are given in Table 2. Assuming that the object is a 2:3 Neptune librator at perihelion, B.G. Marsden computed the orbital elements given in Table 4 (TNO 1). These elements are, of course, relatively uncertain. Nevertheless, it is interesting to note the high orbital inclination value (32.9°) would be the highest inclination of any known TNO. With an assumed red geometric albedo of 0.04, its diameter must be about 160 km. Fig. 2 is a composite image obtained with the four frames where the object is apparent.

The whole observational data were examined a second time by using the program. The critical parameter of the threshold of detection was fixed to 1.5 times the standard deviation due to the sky background noise. Some false detections appeared, a bit less than 4 for each set of images. The visual examination of the detections permitted to eliminate immediatly nearly all the false detections. Indeed these detections appeared nearly always near a bright star and, sometimes, near a galaxy. Only a very limited number of false detections needed to be examined in more details because they appeared to correspond to very weak objects, may be due to the noise, fortuitously aligned.

Finally two detections appeared to correspond to real faint moving objects. The first one was a new TNO, called TNO 2 (appearing in the field 1), and the second one the TNO already detected by the blinking method and mentioned above. The TNO 2 presents an apparent red magnitude of 23.9±0.3. The apparent positions are given in Table 3 and the orbital elements that can be inferred in Table 4. With an assumed red geometric albedo of 0.04 its diameter must be about 180 km.

It is interesting to compare the number of two TNOs detected in observing three fields of 29′×29′ with a limiting red magnitude $m_R \simeq$24 with the surveys already published. Indeed the more recent published luminosity function of the Kuiper Belt (Jewitt et al. 1998; their Fig. 4) gives an average surface density of about 3 objects brighter than $m_R \simeq$24 per square degree. For the surface corresponding to three fields of 29′×29′ it would give 2.1 visible objects. This is in good agreement with our results.

6. Conclusion

In this paper we have shown that our program, which has the main advantage of usability within a complete astronomical data processing package (MIDAS), can give valuable results in the search for new TNOs. These results permit a much faster and efficient detection of new TNOs than the standard method of blinking. This is a key requirement for a re-observation by other observers and subsequent official registration by the IAU.

Because larger and larger CCDs are being developed, which directly increase the amount of data to process, the type of program described in this paper should see a rapid increase in use inside the astronomical community concerned with the search for new TNOs.

Acknowledgements. The authors are grateful to Dr B.G. Marsden who computed the orbital elements given in Table 4 and to the significant comments of the referee towards improving this paper.

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