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Astrométrie/*Astrometry*

First ground-based astrometric observations of Puck

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Abstract The ten small inner moons of Uranus, discovered in 1986, have so far only been studied from space (Voyager 2, HST). The orbital elements derived from the observations indicate very weakly eccentric orbits for all of them but one (Ophelia). We present here the first ground-based astrometric observations of Puck, performed using an Adaptive Optics system. The long observing sequences permitted by ground-based facilities at ESO-La Silla, Chile (64.S-0289) revealed an eccentricity 100 times larger than previously believed. Such a disagreement with the actual theory may arise from the reduction itself based on the bright moons of Uranus, considered until now as precise astrometric references. To cite this article: P. Descamps et al., C. R. Physique 3 (2002) 121–128. © 2002 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

Puck / astrometry / adaptive optics / orbital resonances

Premières observations astrométriques au sol de Puck

Résumé Jusqu'à présent, les dix petites lunes internes d'Uranus, découvertes en 1986, n'ont pu être étudiées que depuis l'espace (sonde Voyager 2, télescope spatial Hubble). Les éléments orbitaux déduits des observations indiquent pour chacune d'entre elles, sauf une (Ophélie), des orbites très faiblement excentriques. Nous présentons dans cet article les premières observations astrométriques au sol de Puck, le plus important en taille et le plus extérieur des satellites faibles, réalisées à l'aide d'un système d'optique adaptative. Les longues séquences d'observation autorisées par une instrumentation basée au sol à ESO-La Silla, Chili (64.S-0289) ont révélé une excentricité 100 fois supérieure à la valeur actuellement admise. La réalité de cette excentricité reste à confirmer. Elle pourrait résulter de l'utilisation des satellites brillants d'Uranus comme objets de référence dans la réduction astrométrique. Pour citer cet article : P. Descamps et al., C. R. Physique 3 (2002) 121–128. © 2002 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

Puck / astrométrie / optique adaptative / résonances orbitales

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Avec le survol en 1986 du système d'Uranus par la sonde Voyager 2 [1], dix nouveaux petits satellites proches de la planète furent découverts. A partir de ces observations et de celles menées en 1994 par le télescope spatial Hubble, la détermination de leurs éléments orbitaux montrait des orbites quasiment circulaires [2,4,5]. L'absence de résonances connues dans le système d'Uranus explique ce résultat qui provient alors d'un simple effet de circularisation orbitale sous l'action des marées.

Nous avons mené une série d'observations de Puck, le plus brillant des petits satellites internes d'Uranus à l'aide du système d'optique adaptative ADONIS, monté sur le télescope de 3,6 m de l'ESO. Cette technique est l'une des plus performantes pour à la fois renforcer le rapport signal/bruit et améliorer la résolution spatiale [7]. La calibration et l'orientation des images ont été effectuées à partir de la mesure des positions des satellites brillants présents sur l'image au moment de l'observation et dont les positions sont données par la théorie GUST86 [13]. Afin de prendre en compte l'extrême variabilité du fond de ciel au voisinage d'Uranus ainsi que les effets provenant de la correction optique du système, une méthode spécifique de détermination des positions a été mise au point. Cette méthode se base sur l'ajustement aux images des objets d'un modèle de profil stellaire théorique constitué d'une fonction de Moffat et d'une fonction de Gauss ([12], Fig. 2) ainsi que d'une surface polynomiale de degré 2 pour reproduire le fond de ciel. Les résidus en position obtenus sont de l'ordre de 30 millièmes de seconde de degré (mas).

L'analyse des positions astrométriques ainsi obtenues par ajustement d'une orbite képlerienne [15] apparente révèle une valeur de l'excentricité de $0{,}010 \pm 0{,}003$ qui est près de 100 fois supérieure à la valeur actuellement admise (cf. Tableau 1). Bien que les observations faites par le télescope spatial Hubble soient de meilleure qualité (résidu de 10 millièmes de seconde de degré), elles sont essentiellement concentrées en trois zones de l'orbite ne couvrant pas uniformément celle-ci (cf. Fig. 3). Nos observations d'octobre 1999 ne présentent pas cet inconvénient majeur qui a pour principale conséquence de contraindre trop faiblement la détermination de l'excentricité. En définitive, une explication à cette excentricité anormalement élevée de l'orbite de Puck pourrait provenir de la réduction astrométrique utilisant les satellites brillants d'Uranus, parmi lesquels Ariel ne pourrait être considéré comme une référence astrométrique très précise.

1. Introduction

Until 1986, the Uranian system, studied from ground-based telescopes, had only revealed its brightest five moons. The planet flyby by Voyager 2 led to the discovery of ten new satellites about ten times smaller in size located closer to the planet. The outermost eight of them were observed again with the Hubble Space Telescope (HST) in 1994 [2]. The orbital elements derived from the Voyager data [4] and the HST image [2,5] indicate quasi circular orbits, with eccentricities of the order 10^{-4}, except for Ophelia whose eccentric orbit ($e \sim 0.01$) was tentatively attributed to a resonance with the outer edge of the ε ring [3]. Indeed, it is known that planetary satellite orbits are only weakly eccentric. In the well known systems of Jupiter and Saturn, the eccentricity is generally of the order of 10^{-3}, but, under the effect of orbital resonances between satellites which may hamper any circularizing effect of tidal interactions, it approaches or exceeds 0.01 for five of the moons. Such resonances are not observed in the Uranian system.

New improvements in ground-based imaging capabilities have recently allowed detection of small inner planetary moons from Earth [6,7]. One of the most powerful is adaptive optics (AO), aimed to compensate the image degradation by the effect of atmospheric turbulence and to approach the diffraction limit of the telescope (typically 0.09 arcsec for a 3.6 m telescope at 1.6 µm). This also increases by more than a factor of 10 the peak intensity of a point source image. Additionally the better angular resolution significantly improves the signal to noise ratio S/N of a faint object (the moon) nearby a bright one (the planet) by reducing the extension of the planetary glare. Finally the shorter integration time needed for the detection

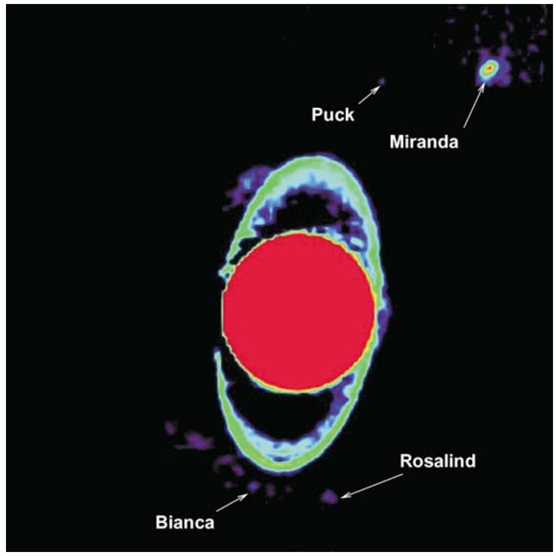


Figure 1. H band image obtained on May 2 1999 at 10:11 UTC with the ADONIS/SHARPII+ system and processed with the MISTRAL deconvolution method [10]; an algorithm especially designed for AO observation of planetary objects. The Epsilon ring and its longitudinal anomaly are clearly detected. The deconvolution process has enhanced the signal from Puck up to a final S/N of 120. Innermost satellites, such as Bianca and Portia, can be also identified sporadically on our dataset.

Figure 1. *Image en bande H obtenue le 2 mai 1999 avec le sytème ADONIS/SHARPII+ et traitée à l'aide de la méthode de déconvolution Mistral* [10]*, un algorithme spécialement développé pour les observations en optique adaptative des objets planétaires. L'anneau Epsilon et son anomalie longitudinale sont clairement détectés. Le processus de déconvolution a permis d'atteindre un rapport signal/bruit final de* 120 *pour Puck. Les satellites internes, Bianca et Portia, peuvent également être identifiés de manière sporadique dans l'ensemble de nos données.*

allows reduction of the smearing effect on moving objects whilst getting on the same plate and at the same time unsaturated bright satellites which may be used as high quality astrometric targets.

2. Observations

We have recently monitored the Uranian system with the ADONIS AO system implemented on the ESO-La Silla 3.6 m telescope. Long duration observing sequences were taken in the J, H, and K infrared broad bands (1 to 2.5 µm) on May 02 (07:28–10:30 UTC) and on 27, 28 and 29 October, 1999 ($\sim$ 00:00–04:00 UTC). Basic data processing, including background subtraction, flat-field correction and bad pixel removal, has been done using the automatic pipeline especially developed for the ADONIS data [8,9]. The data reduction processes and the image analysis have been detailed for the May 1999 data [10]. The bright moons Ariel and Miranda are visible on all the images. Sometimes a third one, either Titania or Umbriel, is also located inside the 25.6×25.6 arcsec field of view. Among the inner satellites, Puck, the outermost one, is always detected with $S/N \sim 5$, then close to the detection limit of this faint object whose J, H, K magnitudes are respectively 20.6, 20.1 and 19.7 [11]. Even when a special AO deconvolution process [10] is applied to the images, the other inner satellites, fainter and closer to the planet, are detected on an irregular basis only, depending on the quality of the AO correction [12] (Fig. 1).

The permanent detection of Puck coupled with a reasonable S/N strongly improves the expected precision of orbital elements determination. An especially favourable situation was reached in October 1999 when images were obtained during three consecutive nights, thus providing a very good coverage of Puck's orbit (orbital period ~ 0.769 days).

3. Astrometric analysis

The accuracy of our astrometric determination depends on a precise location of the satellite on each individual image. With that prospect in mind, we developed a specific centroiding process based on a suitable stellar profile. Much of the flux of the stars and satellites visible on the images is contained within

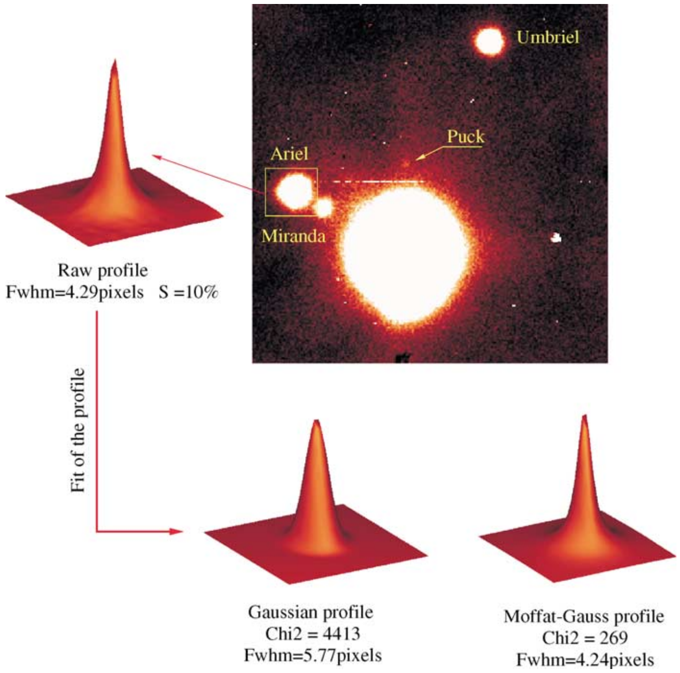


Figure 2. Image taken at the 3.6 m telescope of ESO-La in H band (1.64 µm) on October 28, 1999 at 03:35 UTC (not deconvolved). Three bright satellites, Ariel, Miranda and Umbriel, are visible. Puck is also detected at the northern edge of the planetary disc halo. The raw 3D profile of Ariel is displayed, and compared with a fitted Gaussian profile and a Moffat–Gaussian profile. One can clearly see the improvement in the profile shape brought by our composite profile owing to a better description of the flux repartition in the wings of the satellite image. At this wavelength the diffraction-limited spatial resolution is 0.939 pixels (i.e. 0.0939 arcsec). The Strehl ratio is only 10% for each satellite. Puck's signal-to-noise ratio is ~ 5.

Figure 2. *Image non déconvoluée prise le 28 octobre 1999 à* 03:35 *UTC au télescope de* 3,6 m *de l'ESO-La en bande H* (1,64 µm)*. Trois satellites brillants, Ariel, Miranda et Umbriel, apparaissent nettement. Puck est aussi détecté sur la frontière nord du halo du disque planétaire. Le profil brut 3D d'Ariel est à comparer avec un profil purement gaussien et un profil mixte de Moffat–Gauss. Celui-ci montre sa capacité à reproduire au mieux la forme réelle du profil de l'objet du fait d'une meilleure description de la distribution du flux dans les ailes. A cette longueur d'onde, la résolution spatiale théorique est de* 0,939 *pixels (soit* 0,0939 *secondes de degré). Le rapport de Strehl n'est que de* 10% *sur chacun des satellites. Le rapport signal/bruit de Puck est de l'ordre de* 5.

a small, bright core where the surface brightness is well approximated by a Gaussian function imposed by statistical effects of seeing. But there exists also an extended halo which falls off as an inverse power of radius with an exponent close to 2 and which is probably caused by scattering in the atmosphere and optics corrections of the wavefront [13]. This part of the profile is well represented by a Moffat function (Fig. 2). The radial scale length of the Gaussian and Moffat components differ from frame to frame due to differences in seeing conditions and wavefront corrections. Finally, the residual sky background was modelled by a polynomial surface of degree 2, leading to a good approximation inside the small area around the star. The quality of the model was checked using observed stars and it proved to be valid for Strehl ratios (defined as the ratio of the image peak intensity to the peak intensity of a perfect diffraction-limited image) up to 20%. For larger Strehl ratios a more reliable profile is needed with an additional component such as an exponential function whose physical cause is not intuitively obvious. For bright objects (such as the outer satellites) the accuracy of our centroiding with the Moffat–Gauss function is ~ 0.02 pixels, i.e. 2 milliarcseconds (mas). For fainter objects (such as Puck), close to the detection limit, it reaches 0.3–0.7 pixels, i.e. 30 to 70 mas on average. Comparisons with a simple Gaussian function indicate an improvement by a factor of 2 to 5. The effects of anisoplanatism, of geometric distortion and of relative refraction corrections are negligible compared to the centroiding accuracy. Precise scale calibration and orientation determination of the detector were made using the bright satellites observable in each image, and a classical 6 constants plate model. The GUST86 analytical ephemeris of Laskar and Jacobson [14] gives their positions relative to Uranus with a precision of ~ 10 mas. On average, the observations were acquired with a relatively poor Strehl ratio

($\sim$ 10%) for which the Moffat–Gauss approximation is well suited. The rms residuals (root mean square of residuals computed as the differences between observed and predicted positions) is $\sim$ 30 mas.

4. Orbit determination

In order to reduce the number of parameters to be determined, the orientation of the orbital plane of Puck has been held equal to that given by its ephemeris [5] so that the only remaining elements to be determined are the shape parameters, namely the semi-major axis and the eccentricity, and the position of the apsidal line. Rather than to use a classical model for the satellite orbital motion based on a precessing ellipse referred to the Uranian system [4,5], we simply expressed in a closed form the expression of a Keplerian orbit in the tangent plane [15]. Thanks to this geometric approach of the orbit determination problem, no assumptions were made on the underlying dynamics except that the osculating orbit follows Kepler's first law. Since we can neglect the secular variations of the elements during each observing sequence (< a few days), no changes occur in orbital elements so that an elliptical path may be directly least square fitted to the observations with an algorithm based on the Marquardt–Levenberg technique [16].

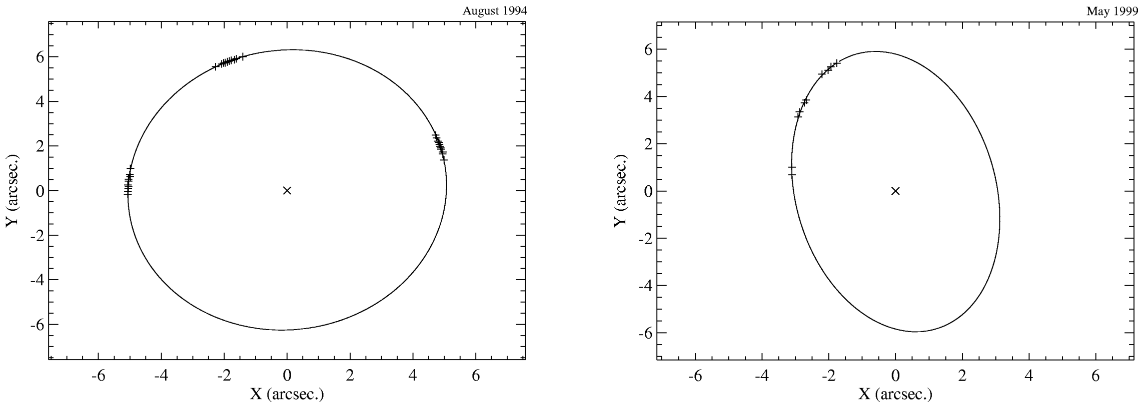
The method was successfully tested on the theoretical orbits of well-known satellites (Mimas, Triton, Miranda) before being applied to Puck. In order to test the consistency of our results, we also independently applied our method to the 1994 published HST data [3]. Table 1 shows the parameters derived from these calculations and the quality of the fit. The uncertainty estimates are square-root results of the diagonal elements of the covariance matrix (i.e. formal errors). The fitted orbits are plotted on Fig. 3. The figure shows that our October 1999 data are more or less uniformly distributed all along the orbit, whose parameters can therefore be tightly constrained, whereas the HST data are concentrated within three zones distributed over half an orbit only, clearly providing much weaker constraints on the orbital parameters, in particular on the eccentricity. Our fit of HST data clearly shows a good agreement with the actual adopted values for the semi-major axis (86004 ± 0.064 km) and the eccentricity (0.00012 ± 0.000061). On the other hand, the fit of the October 1999 observations reveals an astonishing eccentricity of 0.010 ± 0.003.

The χ^2 test is an efficient tool for testing the goodness of the fit only in the case where observations are normally distributed but it does not allow taking into account effects of systematic errors. Therefore in order to control the reliability of our results, we applied the transformation from the apparent orbit toward the true orbit using the position in space of the orbital plane as given by the ephemeris. The angle chosen for the representation is the argument of the latitude, which is the angle of the body's direction on its orbit with respect to the direction given by the intersection of the orbital plane with the equatorial plane of Uranus. This direction may be considered as fixed in space for the 1999 observations. The 1999 data have been put

Table 1. Semi-major axis a and eccentricity e of Puck's orbit with their 1σ uncertainties obtained by least-square fit of a Keplerian orbit on the ADONIS and HST observations. The three datasets have been fitted separately. The quality of the best fit is measured by the value of the reduced χ_r^2 (summed square errors normalized to the number of degrees of freedom which is equal to the number of observations minus the number of parameters of the model).

Tableau 1. *Demi-grand axe a et excentricité e avec leurs incertitudes 1σ de l'orbite de Puck obtenus par ajustement par moindres carrés d'une orbite képlérienne aux observations ADONIS et HST. Les trois ensembles de données ont été ajustés séparément. La qualité de l'ajustement est mesurée par la valeur du χ_r^2 (somme des carrés des erreurs normalisée au nombre de degrés de liberté qui est égal au nombre d'observations moins le nombre de paramètres du modèle).*

Orbital elements	October 1999	May 1999	1994 HST data
a (arcsec)	6.007 ± 0.009	6.019 ± 0.048	6.324 ± 0.004
a (km)	86085 ± 129	87176 ± 692	86104 ± 57
e	0.010 ± 0.003	0.015 ± 0.009	0.0014 ± 0.0005
χ_r^2	1.25	1.28	1.07



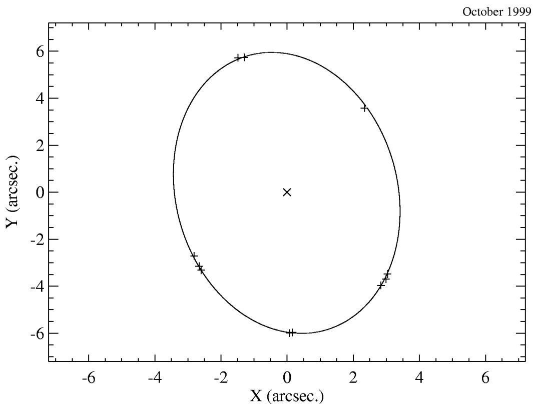


Figure 3. Observed positions of Puck relative to Uranus' center in the tangent plane and analytical orbits fitted by least squares minimisation for our 1999 observations (ADONIS) and for the July 1994 HST ones. Note that the shape of the model orbit differs in both cases (more circular in the case of HST) because it is the 'apparent orbit' in the plane normal to the line of sight, whose orientation has changed between the observations.

Figure 3. *Positions observées dans le plan tangent de Puck relativement au centre d'Uranus et orbites analytiques ajustées par la méthode des moindres carrés pour les observations de 1999 (ADONIS) et de juillet 1994 (HST). La forme apparente de l'orbite diffère dans chacun des cas en raison du changement d'orientation et d'échelle du plan normal à la ligne de visée entre chaque observation.*

together in the orbital plane of the October 1999 observations. To do this we translated the May 1999 data by the angle of which the pericenter has turned between the two epochs. This angle may be derived from the knowledge of the apsidal rate [5]. Resulting data are plotted on Fig. 4. The elliptical orbit fitted to the October 1999 data (cf. Table 1) has been superimposed onto the whole set of 1999 data as well as the value of the actual semi-major axis. The HST data do not show a sinusoidal behaviour like the 1999 data.

5. Discussion

Like Pascu et al. [2], we used the bright Uranian moons, mainly Miranda and Ariel, as astrometric references to calibrate the scale and orientation of the CCD frames due to the lack of catalogued stars in the field of the observations (25 arcsec). Such a method is very efficient provided that ephemeris positions of the satellites are accurate to a tenth of mas. However recent observations of Ariel seem to exhibit anomalously large residuals with the ephemeris GUST 86 of at least 50 mas (R. Carlos, personal communication). Given the fact that Jacobson built the refined ephemeris of Puck from a combined analysis of the HST and Voyager 2 observations, this may both explain the coherence of our HST observations analysis with the actual set of orbital elements and the derivation of an eccentricity in the 1999 observations. Indeed, the Puck ephemeris may be biased by inaccurate positions of Ariel during the reduction of the HST data which may give rise to an apparent eccentricity in its orbit since we used the position of the orbital plane in space as given by the ephemeris.

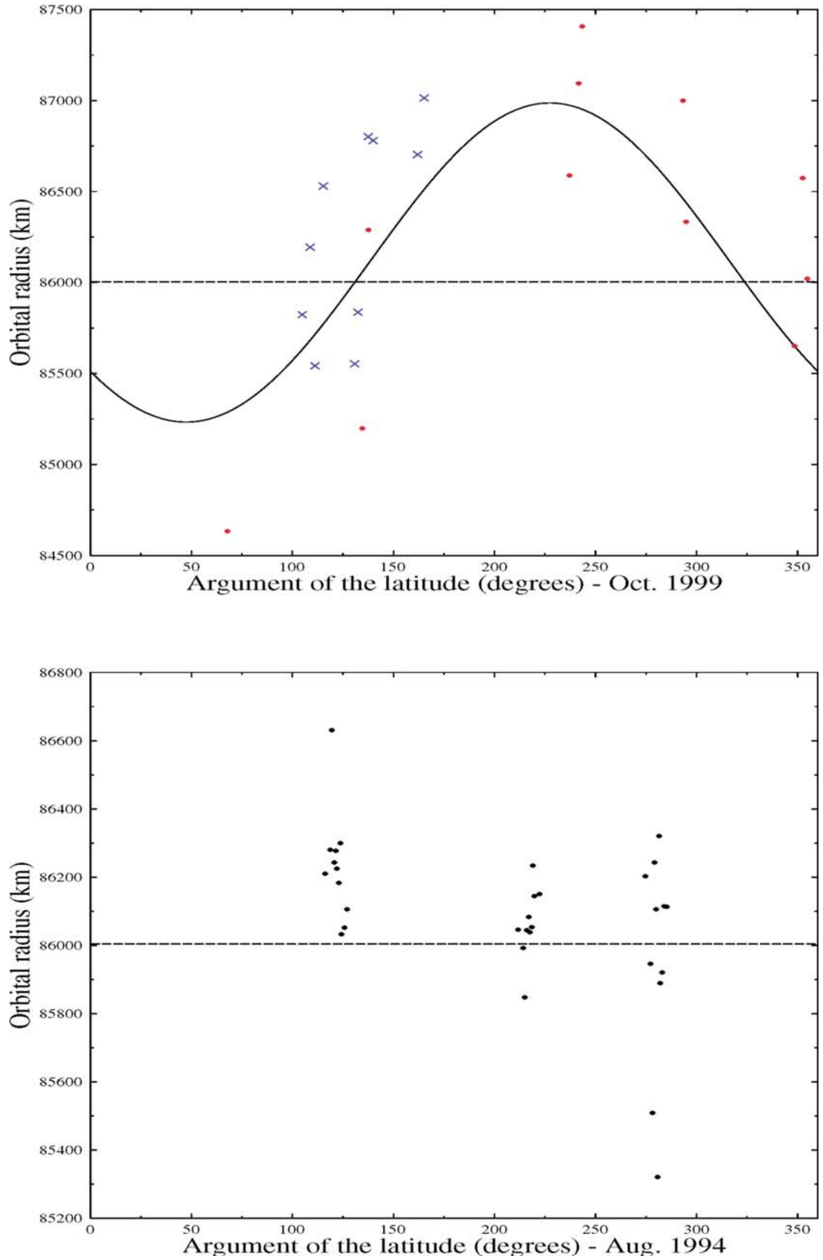


Figure 4. Plot of the HST and ADONIS projected data in the Puck orbital plane. May 1999 data are plotted with crosses and October 1999 with dots. 1994 observations confirm a quasi-circular orbit whereas our 1999 observations seem to show a sinusoidal behaviour, characteristic of an elliptical orbit with a significant eccentricity.

Figure 4. *Projection dans le plan de l'orbite de Puck des observations de 1994 faites avec le HST et de celles de 1999 faites à l'ESO. Pour les observations de 1999, les données de mai sont représentées avec des croix tandis que les données d'octobre le sont avec des points. L'orbite de Puck est actuellement considérée comme quasi circulaire ce qui devrait entrainer une répartition des points de mesure autour d'une droite horizontale avec un rayon orbital de* 86 004 km. *Les observations de 1994 semblent confirmer ce fait mais ce n'est pas le cas pour celles de 1999 qui se répartissent assez nettement le long d'une sinusoide, caractéristique d'une orbite nettement non-circulaire.*

6. Conclusion

Adaptive optics is suitable for the astrometry of faint objects near a bright primary. The only actual limitation is the field size. Ephemeris positions of the bright satellites with an accuracy of 10 mas or better are used to implement a plate constants solution for scale, orientation and coordinate origin. In our case the suspected degraded ephemeris of Ariel may be the origin of systematic errors due to uncalibrated scale and orientation errors.

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