

Surface characterization of 28978 Ixion (2001 KX₇₆)^{*}

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Abstract. The Plutino 28978 Ixion, one of the largest objects in the Kuiper Belt, is measured by *R* filter photometry and linear polarimetry over the phase angle range as well as by *BVRI* colours and visible spectroscopy. Ixion is a medium red object with spectral slope of 17.7%/100 nm (400–900 nm). While its opposition phase curve surge (0.2 mag/deg) is within the typical range found for other solar system objects, it displays unusually high negative polarization (min. –1.3%). Comparison with model spectra and numerical modeling of the opposition brightening and polarization effects suggest an areal mixture of absorbing (dark) and icy (bright) compounds on its surface: the mixing ratio is about 6:1 for dark and bright material of 0.21 and 0.79 single-scattering albedo and of 250 and 33 dimensionless mean free path (length multiplied by wave number), respectively.

Key words. transneptunian object – 28978 Ixion: 2001 KX₇₆ – surface properties

1. The Plutino 28978 Ixion (2001 KX₇₆)

Transneptunian objects (TNOs) are believed to represent the most primordial objects from the formation period of the Solar System that are accessible to ground-based observations. Yet, TNOs are faint (typically $V > 20$ mag), hence difficult to observe. Studies of their surface composition are cumbersome and require the use of 8–10 m class telescopes. In particular, their characterization by polarimetric observations was not yet attempted since feasible only now by means of this new telescope generation and its sophisticated instrumentation.

The TNO 28978 Ixion, discovered in 2001 and preliminarily designated as 2001 KX₇₆, belongs to the dynamical class of Plutinos, orbiting the Sun in 2:3 resonance with Neptune. Ixion seems to be one of the largest TNOs found so far. Radio observations combined with visual brightness estimates (Altenhoff et al. 2004) provide an upper limit of 804 km for the diameter and a geometric albedo of 15% (based on CBAT magnitudes; see below for our estimates). It seems to be a slow rotator with a lightcurve amplitude of less than 0.15 mag, however the exact rotation period could not yet be determined (Ortiz et al. 2003). A near-IR spectrum of Ixion taken by Licandro et al. (2002)

is flat and featureless in *H* and *K* bands and displays a medium-steep slope towards the short wavelength end of the *J* band. Visible spectra (Marchi et al. 2003) show an intrinsic reddening of the surface of 17.9%/100 nm and display a weak absorption feature at 800 nm of uncertain origin.

Here, we present new observations of the Plutino 28978 Ixion obtained at the ESO Very Large Telescope (VLT): polarimetry – the first one ever obtained of a TNO –, photometry and spectroscopy in the visible wavelength range. These new observations complement the existing observational database of the object and allow us a first synoptic modeling interpretation of the surface of this Plutino.

2. Observations and data reduction

2.1. Observations

New observations of 28978 Ixion were taken with the FORS1 instrument (see <http://www.eso.org/instruments/fors1>) at the 8.2 m VLT Unit Telescope 3 (Melipal). We obtained *BVRI* photometry, low-dispersion spectroscopy in the range 350–1000 nm (grism 150I: spectral resolution 200 for a 1'' slit), and a series of *R* filter linear polarimetry and *R* filter photometry.

Spectroscopy and *BVRI* photometry were obtained quasi-simultaneously (within 1 h) on May 6, 2002, in visitor mode.

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^{*} Based on observations collected at the ESO VLT within programs 69.C-0133 and 167.C-0340.

Table 1. Observing log and results of VLT observations of 28978 Ixion: *R* band photometry and polarimetry time series (left), and multicolour photometry (right). Sun = solar distance, Earth = distance to Earth, Phase = angle Sun-TNO-observer. Sky conditions: THN = thin cirrus, CLR = clear, PHO = photometric.

R band polarimetry and photometry time series										BVRI	
Date (dd/mm/yy)	04/04/02	20/04/02	06/05/02	12/05/02	08/06/02	16/06/02	07/07/02	09/07/02	30/08/02	Date	11/05/02
Start/end (UT)	07:45/10:10	07:06/09:32	07:04/09:28	05:36/08:00	04:31/06:55	03:18/05:45	03:54/06:19	03:53/06:16	23:50/02:14	Start/end	03:26/04:35
Sun (AU)	43.13	43.13	43.12	43.12	43.10	43.10	43.08	43.08	43.05	Sun	43.16
Earth (AU)	42.46	42.33	42.17	42.14	42.10	42.13	42.29	42.31	43.07	Earth	42.15
Phase (deg)	1.07	0.81	0.50	0.37	0.25	0.43	0.85	0.88	1.34	Phase	0.40
R/σ_R (mag)	19.82 ± 0.03	19.68 ± 0.02	19.64 ± 0.03	19.59 ± 0.03	19.59 ± 0.03	19.55 ± 0.04	19.73 ± 0.03	19.73 ± 0.03	19.76 ± 0.04	R/σ_R (mag)	19.61 ± 0.02
q/σ_q (%)	-1.10 ± 0.11	-0.84 ± 0.11	-0.51 ± 0.11	-0.43 ± 0.05	-0.28 ± 0.05	-0.16 ± 0.17	-0.85 ± 0.15	-0.86 ± 0.18	-1.30 ± 0.17	B/σ_B (mag)	21.24 ± 0.02
u/σ_u (%)	0.20 ± 0.14	0.06 ± 0.14	-0.14 ± 0.13	-0.10 ± 0.21	-0.02 ± 0.11	0.09 ± 0.14	-0.10 ± 0.13	0.01 ± 0.15	0.02 ± 0.21	V/σ_V (mag)	20.21 ± 0.02
Sky	PHO	PHO	THN	CLR	THN	PHO	PHO	PHO	PHO	Sky	PHO

R filter polarimetry and photometry were obtained in service mode, covering the phase angle range from 1.1° pre- to 1.3° post-opposition at various epochs. Ordinary and extra-ordinary beams of the object field of view were exposed simultaneously with equal integration time of 450 s at 16 angles of the $\lambda/2$ retarder plate ($0^\circ, 22.5^\circ, 45^\circ, \dots, 337.5^\circ$, with respect to celestial coordinate system). The acquisition sequence for imaging polarimetry with FORS1 allowed us to obtain additional broadband images (without polarization optics) to measure the *R* filter brightness of the object.

The usual calibration exposures were taken at each observing epoch, i.e., apart from biases for each observing mode, sky flatfields and photometric standard stars for photometry, screen flatfields, arc exposures, spectrophotometric standards and 2 solar analog stars for spectroscopy (Landolt 98-978, Landolt 102-1081; both observed twice per night). Polarized and unpolarized standard stars were regularly observed as to make sure that the polarimetric optics were correctly oriented and that instrumental polarization was below the 10^{-3} level.

2.2. Data reduction

The reduction for the photometry and spectroscopy follows the procedure described in Boehnhardt et al. (2002) and Barucci et al. (2002), respectively, and references therein. End products of the photometry reduction are filter magnitudes, colours and spectral gradients, of the spectroscopy reflectivity spectrum and spectral gradients.

The reduction procedure for polarimetry includes bias and flatfield corrections (flatfields are sky images taken at twilight time with no polarimetric optics in the light path). Estimates of Stokes q and u , normalized to Stokes I , and defined as in Shurcliff (1962) and with q positive along the North Celestial Meridian) are obtained by calculating

$$q_{ij} = \frac{1}{2} \left\{ \left(\frac{f^o - f^e}{f^o + f^e} \right)_{\alpha=(i-1) \times 45^\circ} - \left(\frac{f^o - f^e}{f^o + f^e} \right)_{\alpha=(j-1) \times 45^\circ} \right\}$$

and

$$u_{ij} = \frac{1}{2} \left\{ \left(\frac{f^o - f^e}{f^o + f^e} \right)_{\alpha=(i-1) \times 45^\circ + 22.5^\circ} - \left(\frac{f^o - f^e}{f^o + f^e} \right)_{\alpha=(j-1) \times 45^\circ + 22.5^\circ} \right\}$$

$$i = 1, 2, 3, 4; j \neq i,$$

where f^o and f^e are the (background subtracted) counts in the ordinary and extraordinary beam, respectively, and α indicates the position angle of the retarder waveplate. The median and the standard deviation σ of the q_{ij} and u_{ij} distributions are calculated, and a σ -clipping algorithm is used to reject those q_{ij} and u_{ij} values that deviate more than 1.5σ from the median of the q_{ij} and u_{ij} distributions. The final Stokes parameter estimates q' and u' are calculated by averaging the remaining (non rejected) q_{ij} and u_{ij} values. We then transform q' and u' into q and u , the Stokes parameters with respect to the light scattering geometry, according to

$$\begin{aligned} q &= \cos(2\Theta) q' + \sin(2\Theta) u' \\ u &= -\sin(2\Theta) q' + \cos(2\Theta) u'. \end{aligned} \quad (1)$$

Here Θ is the angle between the direction Ixion-North Pole and the direction Sun-Ixion, increased of 90° . Note that q represents the flux perpendicular to the scattering plane minus the flux parallel to that plane, divided by the sum of the two fluxes. For 28987 Ixion, all our measurements of q are negative, the ones for u are basically zero within the error bars. Thus, the maximum polarization falls essentially in the light scattering plane defined by the triangle Sun-Ixion-Earth. Table 1 lists the results of the photometry and polarimetry measurements.

3. Results and interpretations

Absolute magnitude, colours and spectra of 28978 Ixion: 28978 Ixion has an absolute *R* magnitude of $H_R = 3.24$ mag (scaled to 1 AU Sun and Earth distance and extrapolated to zero phase angle – see Fig. 2; Bowell et al. 1989). This implies geometric albedos of about 0.08 in *V* and 0.10 in *R* (assuming the upper limit for the diameter by Altenhoff et al. 2004). According to the *BVRI* colours ($B - V = 1.03 \pm 0.03$ mag, $V - R = 0.60 \pm 0.03$ mag, $R - I = 0.42 \pm 0.03$ mag), 28978 Ixion is a medium red TNO with a spectral gradient (*BVRI*) of $17.7 \pm 3.8\%/100$ nm, i.e. close to the maximum in the reddening distribution of the Plutinos (Boehnhardt et al. 2004). On May 6, 2002, it showed a featureless spectrum (Fig. 1) of constant slope ($19.8\%/100$ nm) between 400–650 nm and shallower gradient from 800–930 nm ($11.7\%/100$ nm). The spectral slopes determined from our observations are in agreement with those of Marchi et al. (2003) measured from spectroscopy of the object obtained the night before ours. However,

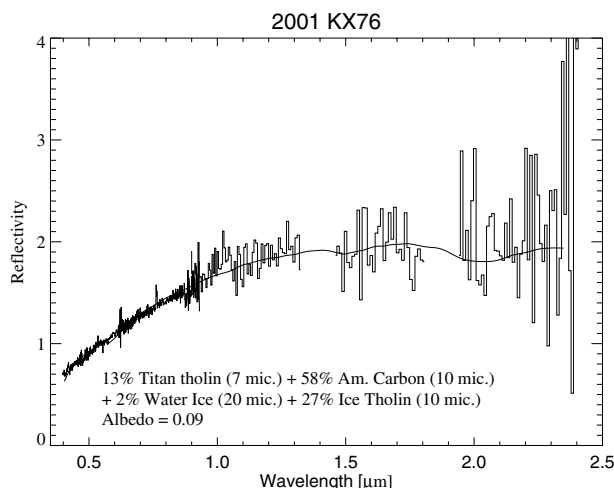


Fig. 1. Combined visible (our work) and near-IR (Licandro et al. 2002) spectrum of 28978 Ixion. The continuous line shows the best fit model with the areal mixture of compounds as indicated in the figure. The reflectivity spectrum is normalized to unity at 550 nm.

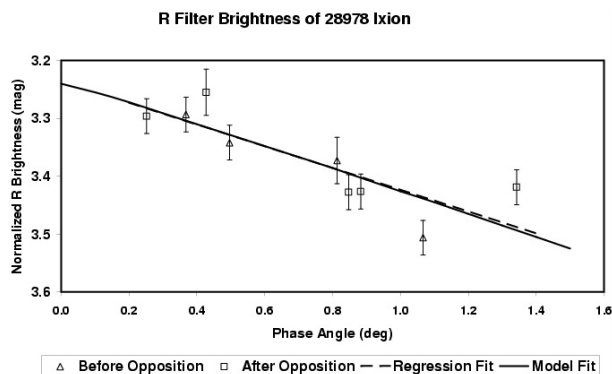


Fig. 2. Opposition R filter phase curve of 28978 Ixion. The normalized (for 1 AU Sun and Earth distance) magnitude of the object is plotted versus phase angle, suggesting an absolute R filter magnitude of $H_R \approx 3.24$ mag. Broken line = best linear fit, solid line = modeling results.

we cannot confirm their detection of a shallow absorption feature around 800 nm. The available spectra may support the scenario of a heterogeneous surface composition of 28978 Ixion, as already found in two other Plutinos (de Bergh et al. 2004; Lazzarin et al. 2002).

Interpretation: We combined our visible data with the near-infrared spectrum of Licandro et al. (2002). The combined spectrum covers the wavelength range 0.4–2.4 micron. To interpret this spectrum in terms of possible surface composition we apply the same procedure already used by Cruikshank et al. (1989), Barucci et al. (2002) and Dotto et al. (2003a,b) to obtain model spectra of simple areal mixtures of organics (kerogen, tholins, amorphous carbon), minerals (pyroxenes, olivine), and ices. For each combination of compounds and percentages, albedo and spectra were computed and compared with the measured data. Assuming the mean albedo value of 0.08 (see last paragraph), our best model (Fig. 1) corresponds to an areal mixture of 13% titan tholin, 65% amorphous carbon, 20% ice tholin, and 2% water ice. Ice tholins (McDonald et al. 1996) and titan tholins (Khare et al. 1993, and references therein)

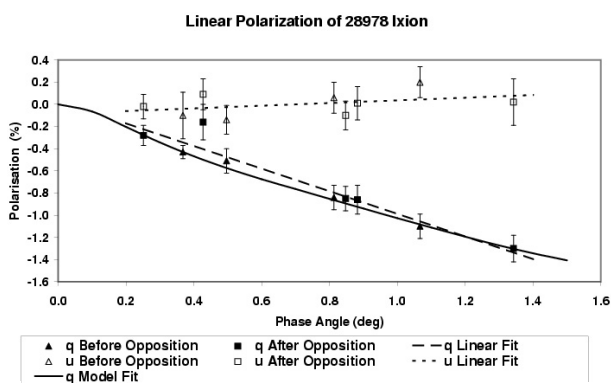


Fig. 3. Phase angle resolved polarimetry of 28978 Ixion. The figure shows the Stokes q and u as determined with respect to the light scattering plane coordinate system, measured over the phase angle range of the object. Broken line = best linear fits with slopes $-1.02 \pm 0.02\%/deg$ for q and 0.21 ± 0.08 for u , solid line = modeling results.

are synthetic macro-molecular compounds produced from an icy mixture of H_2O and C_2H_6 and a gaseous mixture of N_2 and CH_4 . Tholins have visible albedo of 0.04. They have already been used as color agent to model the surface composition of TNOs and Centaurs (Dotto et al. 2003a,b, and references therein), in particular to achieve the red continuum of the visible part of the spectrum. Amorphous carbon (Zubko et al. 1996) is a dark featureless compound often used to model spectra of dark surface objects (Barucci et al. 2002). The water ice bands at 1.5 and 2 micron are somewhat uncertain, but the suggested combination of ice tholins and water ice is the most likely possibility to reproduce the observed spectral behaviour between 1 and 2.4 micron.

Opposition brightening and linear polarization: The polarimetric observations indicate that the reflected light of 28978 Ixion is polarized in the scattering plane of the object with a steeply descending degree of linear polarization q with increasing phase angle. The slope is $\sim -1\%/degree$ (identical pre- and postperihelion) with the minimum value of -1.3% at the (maximum) phase angle of 1.3 degrees (Fig. 3). The actual minimum polarization appears not to be covered by the observations. The polarimetric phase curve of 28978 Ixion is unique among those observed for solar system objects and resembles experimental measurements (e.g., Shkuratov & Ovcharenko 2002) for samples of smoked MgO (extremely bright material) and samples of carbon soot (extremely dark material).

The photometric observations show a steeply increasing brightness toward the zero phase angle, with a slope of ~ 0.2 mag/degree (Fig. 2), rather symmetric to opposition. It is of interest that both sets of observations (i.e. the photometry and the polarimetry) can be fitted by simple straight lines. The scatter of the brightness values around a linear fit line is small, suggesting that the variability due to rotation is small, thus confirming the lightcurve analysis of the object, published by Ortiz et al. (2003). The determination of the rotation period led to inconclusive results due to the insufficient coverage of the actual rotation phase and due to the long time gap to other

photometric data of the objects (Drechsel & Ortiz, private communication).

The slope of the photometric phase curve is in agreement with the relevant parts of the opposition effects observed for many atmosphereless solar system bodies (Rosenbush et al. 2002), including two TNOs, some details of the Moon surface, S-type asteroids, satellites of giant planets, and Saturn's rings. However, Ixion's polarization is very unusual. The polarization observed for the leading (dark) side of Iapetus (-0.8% at 1 deg phase angle; Rosenbush et al. 2002) comes closest to the value for Ixion. The majority of the solar system bodies display polarization values between 0 and -0.5% at 1 deg. The peculiarity of Ixion's polarization is evidence of a specific composition or structure of its surface that could be typical for other Kuiper Belt objects.

Interpretation: In order to explain the observed polarimetric and photometric observations, numerical computations were carried out for coherent backscattering by a spherical asteroid covered by discrete random media of Rayleigh scatterers (Muinonen 2004; Muinonen et al. 2002). The modeling involves two parameters: the single-scattering albedo $\tilde{\omega} \leq 1$ and the dimensionless extinction mean free path $k\ell$ ($k = 2\pi/\lambda$ is the wave number).

As the geometric albedo of Ixion remains uncertain, four single-scattering albedos of $\tilde{\omega} = 0.21, 0.36, 0.56,$ and 0.79 were first chosen for the computations, resulting in the geometric R band albedos of $p_R \approx 0.05, 0.1, 0.2,$ and $0.4,$ respectively. Approximate values for the mean free paths were thereafter found by comparing the observations and the numerical results: with increasing $\tilde{\omega}$, the observations were roughly fitted with $k\ell = 130, 60, 40,$ and 40 . However, using these simple models, it is impossible to reproduce the linearity and the depth of the observed polarimetry. It does appear feasible to fit the observations using conservative Rayleigh scatterers with $\tilde{\omega} = 1.0$ (cf. Mishchenko et al. 2000). For Ixion, however, conservative modeling is ruled out by the slope in the observed spectrum of the object.

Subsequently, keeping the geometric albedo fixed at $p_R = 0.10$, a model was combined from the darkest and brightest random media above (required areal ratio is about 6:1) with $k\ell$ as a free parameter for both components. The resulting bimodal model with $k\ell = 250$ and 33 for the dark and bright components, respectively, is capable of explaining the polarimetric observations (Fig. 3). As to the photometric observations, in addition to brightening due to coherent backscattering, a significant but nevertheless realistic darkening of some 12% per degree due to shadowing effects has been invoked to obtain the theoretical curve in Fig. 2. Note that the photometric slope is still somewhat uncertain so, in reality, the shadowing contribution could be weaker.

Figures 3 and 2 show the tentative fits of the observations using our reference model. These fits have been reached by “eye-balling” within the parameter space available as the emphasis has been to demonstrate the feasibility to explain the observations using a model of coherent backscattering and shadowing. Finally, the polarimetric modeling is in fair agreement with the spectroscopic modeling.

4. Conclusion

We present the first polarimetric measurements of a Kuiper Belt object, 28978 Ixion. These data cover the maximum observable phase angle range of the object as seen from Earth. They are supplemented by the photometric phase curve as well as new visible spectroscopy and photometry. 28978 Ixion seems to be a “normal” medium red Plutino with a regular opposition brightening compared to other solar system bodies. Our albedo estimates in V and R depend on the size of the object for which only an upper limit is known. However, its negative polarization is by far the most pronounced measured in a solar system body so far. Because of a lack of such observations for other TNOs, it is unclear whether or not the high negative polarization of 28978 Ixion is a unique case or typical for this type of objects. Synoptic modeling of these observations including other physical parameters of 28978 Ixion, like albedo, size, rotation variability, suggests that the surface of this Plutino contains an areal mixture of at least two compounds with different single-scattering albedo and micro-porosity. “Areal mixture” just means that bright and dark particles do not interact (as it would be if they were intimately mixed), i.e. they represent separated areas that can cover the surface in a homogeneous manner. As to the extension of the areal variations, any scale length much larger than the given mean free paths and much smaller than the size of the object is allowed. The current reference model (invoking coherent backscattering and shadowing) consists of two parts: (1) a dark component with single-scattering albedo $\tilde{\omega} = 0.21$ and mean free path $k\ell = 250$ and (2) a bright component with $\tilde{\omega} = 0.79$ and $k\ell = 33$. In order to reproduce the geometric albedo of $p_V = 0.08$, potentially close to the true albedo of Ixion the model spherical body must be composed of the dark and bright media components in an areal mixture of about 6:1. The multi-compound composition scenario is compatible with the presence and absence of a shallow absorption feature noticed in the two spectroscopy datasets of the object.

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