Physical properties of PHA 2014 JO25 from a worldwide observational campaign

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ABSTRACT

The study of minor planets is motivated both by fundamental science of Solar system origins (some of these bodies contain the most pristine materials from the early ages of the planetary nebula) and by practical reasons concerning space exploration and impact frequency with Earth. Among minor bodies, near-Earth asteroids are a particularly important group: these objects are nearby the Earth’s orbit and they represent both resources and hazards to humans. This is the case of 2014 JO25. The encounter of this potentially hazardous asteroid with the Earth at 0.011 75 au on 2017 April 19 was a good opportunity to study its properties through photometric and spectral analyses. The work we present here has been carried out thanks to a worldwide observational campaign that included time-series photometry and spectroscopy in the visible and near-infrared wavelengths. The optical images for photometric analysis were collected at different phase angles using small telescopes (<0.5 m) and medium telescopes (from 0.6 to 1.5 m). Spectral analysis was performed by 2–4 m telescopes. The light curve of 2014 JO25 indicates a synodic rotational period of 4.5286 ± 0.0004 h. Although rotational period had been previously obtained by other authors, this work confirms it with a better accuracy. The obtained reflectance spectrum of this asteroid indicates that it belongs to the S-complex and its surface is most likely composed of a mixture of pyroxenes and olivine. From the comparison of its spectrum to those of meteorite samples, as well as from the wavelength position of the first absorption band (close to 0.9 μm), we suggest that this asteroid might contain a large fraction of low-calcium pyroxene and, tentatively, some amounts of metal.

Key words: techniques: photometric – techniques: spectroscopic – minor planets, asteroids: individual: 2014 JO25.

1 INTRODUCTION

The study of near Earth asteroids (NEAs) represents one of the most interesting topics in planetary science, as it could bring insights about the formation of minor bodies and the early stages
of the Solar system. The close approach to the Earth of asteroid 2014 JO25 on 2017 April 19 was a good opportunity to increase our knowledge about potentially hazardous asteroids (PHAs). This target was discovered by the Catalina Sky Survey on 2014 May 5 (MPS 514080), passing at 0.01175 au from the Earth in what was considered as the closest approach of a large (600 m) asteroid after Toutatis in 2004.

Due to its small Earth minimum orbital intersection distance (MOID) of less than 0.05 au, and its large size, i.e. as of 2018 October 9, its absolute magnitude is listed as $H = 17.8^1$ by the JPL Small-Body Database Browser (Gierasch et al. 1994), 2014 JO25 has been classified as a PHA that follows an Apollo-type orbit, highly eccentric and inclined ($e = 0.88$; $i = 25.2^2$), and with a semimajor axis of 2.06 au, a perihelion distance $q = 0.24$ au and an aphelion distance $Q = 3.90$ au.³ Radar observations were conducted by the Arecibo Observatory on 2017 April 19 with a resolution of 7.5 m pixel⁻¹, and by Goldstone radar from April 16 to 21 (Naidu et al. 2017). The radar images show that 2014 JO25 has an irregular shape, suggesting two joined lobes with many concavities and convexities. Based on these observations, it was found that its size was larger than initially estimated (600 m) assuming a spherical shape. Thanks to the radar observations, its maximum axis was set to roughly 1 km. According to observations done by the NEOWISE team (J. Masiero), 2014 JO25 has an optical albedo of about 0.25. This value is in agreement with the one estimated from the near-infrared spectrum obtained by J. Emery, L. McGraw and M. Lucas (University of Tennessee), and C. Thomas (Planetary Science Institute) using the SpeX instrument at the 3.0m McGraw Observatory. The asteroid being classified as an S-type from the near-infrared spectrum obtained by J. Emery, L. McGraw and M. Lucas (University of Tennessee), and C. Thomas (Planetary Science Institute) using the SpeX instrument at the 3.0m NASA IRTF telescope. Both optical albedo value and near-infrared spectrum have not been published but are available at the CNEOS webpage.³

During its 2017 fly-by, 2014 JO25 became very interesting to the scientific community. As it happens with other NEAs, its close approach was a good opportunity to study in detail its physical properties (Müller et al. 2004, 2017; de León et al. 2013). Therefore, we carried out photometric and spectroscopic observations in a worldwide coordinated campaign between 2017 April 20 and May 17 in order to study this object. These observations as well as the data reduction are described in Section 2. Based on our obtained light curve data, we analyse in Section 3 possible reasons for its rapidly changing light curve, among which its binary nature and a potential non-principal axis rotation (Pravec et al. 2005) are considered. The results of the spectroscopic observations are presented and analysed in Section 4.

This work has been carried out in the frame of the European Near Earth Asteroid Research (EURONEAR)⁴ and is the result on an international cooperation between observatories located in different continents and latitudes, such as Europe, Australia and Americas. Without this cooperation, this research would have been impossible due to the trajectory of 2014 JO25 (in both hemispheres) and its very fast fly-by.

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1. https://ssd.jpl.nasa.gov/sbdb.cgi#top
2. https://www.minorplanetcenter.net

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2 OBSERVATIONS AND DATA REDUCTION

Asteroid 2014 JO25 was observed in 13 different nights, from 2017 April 20 to May 7. Nine observing facilities (public and private) were used to take CCD images in order to provide a wide coverage of the asteroid rotation: the 0.8 m IAC80 telescope (Teide Observatory, Tenerife, Spain); the 1.5 m T150 telescope (Sierra Nevada Observatory, Andalucía, Spain); the 0.8 m T80 telescope (La Hita Observatory, Toledo, Spain); the 0.4 m ASH2 telescope (San Pedro de Atacama Celestial Explorations Observatory - SPACEOBS, Chile); the 0.35 m telescope (Isaac Aznar Observatory, Spain); the 0.35 m telescope (Blue Mountains Observatory, Australia); the 0.32 m telescope (JBL Observatory, Australia), the 0.30 m telescope (Darling Range Observatory, Australia), and the 0.30 m CS3-Palmer Divide Station Landers (USA). Details of the telescopes used and equipment specifications are presented in Table 1.

Due to the fast movement of the asteroid in the sky, mainly during the first nights after the asteroid closest approach to the Earth (April 17), we used short integration times. The integration time for each image was fixed taking into account the asteroid’s apparent velocity and visual magnitude, with the aim of obtaining the optimum signal to noise. The minimum integration time was 5 s during April 20 for images captured by Palmer Divide Station CS3 and 10 s for images captured by Observatorio Isaac Aznar T35 telescope during the same night. The maximum integration time was 400 s for images acquired by the Observatorio de Sierra Nevada T150 telescope during May 17, when the asteroid reached an apparent visual magnitude $m_V = 19.02$. This maximum integration time was consistent with the maximum time recommended in order to avoid a smooth light curve (Pravec et al. 2000). The observing circumstances of each run are presented in Table 2. The asteroid proper motion, geometric distance, and phase angle were obtained from the Minor Planet Center, while latitude and longitude phase angle bisectors (PABs) were extracted from the JPL HORIZON Web-Interface. The PAB is the direction that points mid-way between the asteroid-Earth and asteroid-Sun directions, as it would be seen by an observer located on the asteroid (Slivan, Bowsher & Chang 2003).

All data were reduced using MPO Canopus² V10. Images were bias and flat-field corrected. In the case of images obtained with the Isaac Aznar Observatory T35, CS3-Palmer Divide Station Landers T30, Blue Mountains Observatory T35, and Darling Range Observatory T30 and T35 telescopes, dark frame correction was also included in the image calibration process.

Differential aperture photometry was obtained. The photometric reference catalogue was MPOSC3, provided with MPO software. This catalogue is a hybrid of the Sloan Digital Sky Survey (SDSS) and Carlsberg Meridian Catalog, and contains about 150-M type stars. Current version of this catalogue includes, when available, SDSS $g$, $r$, $i$, $z$ magnitudes in addition to BVRI ones, and reports a photometric average error around 0.05 mag. Solar type comparison stars in the field were selected during differential photometry reduction. Although all observations were carried out using a clear filter in order to maximize the asteroid light flux signal, $V$ magnitudes of comparison stars were selected to obtain the calibrated $V$ magnitude of the asteroid. Light-travel time to Earth was considered to correct the time of each image. Finally, a Fourier analysis (Harris et al. 1989; Pravec, Šarounová & Wolf 1996) included in MPO Canopus was used to search for the rotation period of the asteroid that best

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1. https://ssd.jpl.nasa.gov/sbdb.cgi#top
2. https://www.minorplanetcenter.net

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Several light curves of the asteroid were obtained during 13 nights from 2017 April 20 to May 17. The analysis of this photometric data set is not trivial. The shape of the light curve is not the typical one with 2-maxima and 2-minima shown by most asteroids. As discussed in Section 1, 2014 JO25 presents a complex shape, formed by two lobes and with several concavities. In addition, during its close approach to the Earth (mainly from April 20 to 22) the geometry of the observations (in particular the aspect angle), and thus the shape of the observed light curve changed very rapidly (Zappala..)

3 PHOTOMETRIC RESULTS

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et al. 1990). Finally, changes in the PAB among data from different observatories, especially in latitude, imposed additional difficulties in the composition of the light curves (Harris et al. 2014). Taking all these factors into account we have composed the light curves for 2014 JO25 using data from similar geographical coordinates obtained during restricted periods of time in order to reduce the effect of the asteroid changing aspect.

To derive the rotation period, we used a restricted data set using the observations done with the Teide IAC80, La Hita T80, and Isaac Aznar T35 telescopes from April 21 to 24 (marked with an asterisk in Table 2. The Fourier analysis provided a best fit with a synodic period of $P_{\text{rot}} = 4.5286 \pm 0.0004$ h (Fig. 2). The periodogram shows two possible rotation periods: the first one ($4.5286 \pm 0.0004$ h) is the one we adopted. This period provides the lower rms error. The second one is 9.056 h which is double of the first one, and it is likely an alias. Our derived rotational period is similar that of $4.53 \pm 0.02$ h obtained by Warner (2017), using data of the Palmer Divide Station CS3 alone and to that of $4.530 \pm 0.002$ obtained by Tan et al. (2018), but with a higher accuracy. The composed light curve shown in Fig. 3 presents a complex shape as expected,
with a maximum amplitude of 0.19 mag. The obtained rotational period is quite typical for NEAs in the given size range (Pravec & Harris 2000; Pravec, Harris & Michalowski 2002). The amplitude is on the low side of the amplitude distribution for NEAs with periods of 4–5 h. Therefore, 2014 JO25 is either more spheroidal than typical for NEAs of similar sizes and rotation rates (which might suggest something about its origin), or we observed it at an aspect not very far from pole-on that lowered its amplitude. Considering the double-lobed shape of the asteroid from radar images, the second explanation is the most suitable. We calculated the light-curve amplitude at zero phase angle using the expression $A(0^\circ) = A(\alpha) / (1 + ma)$, where $A$ is the amplitude and $m$ is a slope parameter (Zappala et al. 1990), known to be 0.03 for S-type asteroids. With the corrected amplitude and assuming a simple triaxial body model with $a > b > c$ and that the object rotation is about the $c$ axis, we estimated a lower limit for the $a/b > 1.11$.

In Fig. 1, we present the composite light curves obtained for different periods of time using $P_{\text{rot}} = 4.5286$ h. The variations in the shape of the light curves previously reported by Warner (2017) is very obvious, in particular from April 20 to 21, during the closest approach to the Earth of the asteroid. As explained above, these light-curve variations are somehow expected due to the complex shape of 2014 JO25 and the rapid variation of the aspect angle during its close approach.

Another alternative explanation for the observed change in the shape of the light curves every 2 or 3 d is the possible binary nature of 2014 JO25 (Pravec et al. 2016). To study this, we used the iterative subtraction process described in Pravec et al. (2006). We applied it to a restricted set of high-quality data with photometric errors less than 0.03 mag and we found that the light curve appeared periodic on intervals with lengths of up to 2 d with no deviations from the mean light curve that would be caused by a satellite or a non-principal axis rotation of the asteroid. The apparent light curve changes over longer intervals were likely related to a changing viewing geometry of the complex-shaped asteroid observed close to the Earth. Therefore, the light-curve variations seem to be caused by the signature of the shape of the asteroid, with large concavities, on the evolving illumination and viewing geometries. Further modelling using all published light curves and the radar observations could be used to retrieve a good shape model and derive better rotational properties of this asteroid.

4 SPECTRAL OBSERVATIONS

Spectral observations were done with the 2.54 m Isaac Newton Telescope (INT) and the 3.58 m Telescopio Nazionale Galileo (TNG), both located at the El Roque de los Muchachos Observatory, in La Palma (Canary Islands, Spain). The observations were performed on the night of 2017 May 3 with the TNG and 2017 May 4 with the INT. During both nights, the humidity was high ($\approx$80 per cent) and the seeing was variable (between 1 and 2 arcsec). The observational details are shown in Table 3.

Visible INT spectra were obtained with the IDS (Intermediate Dispersion Spectrograph) using the R150 grism diffraction element and the EEV10 CCD camera. A slit of 1.5 arcsec width (about 4 pixels) was set as a trade-off between the variable seeing and resolution. This configuration allows to cover the spectral interval $\sim$0.4–0.9 $\mu$m with a dispersion of 0.4 nm pixel$^{-1}$. All observations were performed by orienting the slit at parallactic angle to minimize the effects of atmospheric differential refraction, and the tracking of the telescope was set at the asteroid’s proper motion. We obtained 5 spectra of 1200 s of exposure time each. We also observed a total of three G2V solar analogue stars in the same airmass range as that of the object: Landolt SA 102-1081 (Landolt 1992), HD 106042, and HD106061.

Images were bias and flat-field corrected using standard procedures. The two-dimensional spectra were extracted, sky background subtracted, and collapsed to one dimension. All these steps were done using IRAF. Each image was visually inspected to avoid the contamination with background stars or movement of the object out of the slit. The wavelength calibration was performed using emission lines from Cu-Ar and Cu-Ne lamps. The asteroid spectrum was divided by the individual spectrum of each solar analogue. The resulting reflectance spectra presented no variations when compared...
to each other, and so, they were all averaged and normalized to unity at 0.55 μm. The error bars correspond to 1σ deviation of the average. The spectrum of 2014 JO25 best matches the spectra of L6 ordinary chondrites (red line).

Near-infrared TNG spectra were obtained with the low-resolution mode of NICS (Near Infrared Camera Spectrograph), based on a HgCdTe Hawaii 1024 x 1024 array. We used the Amici prism disperser that provides a complete 0.9–2.4 μm spectrum, with a 1.5 arcsec slit width. As in the case of visible observations, the slit was oriented in the parallactic angle and the tracking was set at the asteroid’s proper motion. The acquisition followed the typical nodding procedure: we obtained an image of 90 s in one position (position A) of the slit and then we offset the telescope by 10 arcsec in the spatial direction to obtain another image (position B). This process was repeated, and a total of 11 ABBA cycles were acquired. To correct for telluric absorptions and to get the reflectance spectra of the asteroid, two G2V solar analogue stars were observed at the same airmass as that of the object: P041C (Colina & Bohlin 1997) and Landolt SA102-1081.

Images were flat-field corrected and AB pairs were obtained by subtracting consecutive A and B images. Details on the subtraction process can be found in Licandro, Oliva & Di Martino (2001). The one-dimensional spectrum was finally extracted from each AB pair. Wavelength calibration of the individual spectra of the asteroid was performed simultaneously to the division by the spectra of the solar analogue stars, using a specific program developed by the telescope staff and available upon request. As in the case of the visible observations, we verified that there were no significant variations among the resulting reflectance spectra and we averaged them to obtain the final near-infrared spectrum, normalized to unity at 1.6 μm. We merged the visible and the near-infrared spectra (Fig. 4) using the common wavelength region at 0.80–0.85 μm. Our near-infrared spectrum is practically identical to the one reported by CNEOS9 and obtained with the 3.0 m IRTF telescope (Hawaii).

For the taxonomic classification, we used M4AST curve matching tools (Popescu, Birlan & Nedelcu 2012) and SMASS–MIT10 website. According to these tools, the asteroid belongs to the S-complex, and more specifically, it is an intermediate type between an Sr- and a Q-type: the visible part of the spectrum is closer to a Q-type while the near-infrared part resembles that of an Sr-type. This classification is in agreement with the asteroid belonging to the S/Q complex as derived recently by Petropoulou et al. (2018) from visible spectra. However, the wavelength position of the first absorption band is lower than expected for an S/Q-type asteroid.

As a member of the S-complex, the spectrum of 2014 JO25 shows the two strong absorption features centred around 1 and 2 μm associated with silicates (mainly olivine and pyroxene). Using the M4AST tool, we compared the visible and near-infrared spectrum of this object to the more than 2500 reflectance spectra of meteorites available in the RELAB public data base (Pieters & Hiroi 2004). We found that the best three matches correspond to samples of L6 ordinary chondrites: Jackalsfontein (sample ID: MB-CMP-012-L); Tourinnes-la-Grosse (sample ID: MR-MJG-063); and Zavid (sample ID: MR-MJG-063). We have plotted the spectrum of Jackalsfontein L6 meteorite as a red line in Fig. 4. The value of absolute reflectance of this meteorite at 0.55 μm, which is commonly assumed to be roughly comparable to asteroidal geometric albedo, is 0.289, in good agreement with the average albedo of S-complex asteroids (Mainzer et al. 2011), and with the optical albedo of 2014 JO25 obtained from NEOWISE observations (0.25). Actually, the results are very consistent: from the first 25 best meteorite matches provided by the M4AST tool, 18 correspond to L chondrites, and from these, 12 are L6 chondrites. Despite this good agreement, the minimum of the first absorption band for 2014 JO25 is still located at slightly lower wavelengths compared to that of the L chondrites. We discuss about this point in the next paragraph.

Following the methods first described by Cloutis et al. (1986) and Gaffey et al. (1993), we can compute several spectral parameters on the spectrum of 2014 JO25 [wavelength positions of the absorption bands, band area ratio (BAR), etc.] that are related to its composition, and in this way, we can determine mafic mineral abundances on its surface, among other properties. We computed the band minima (B1min and BIImin), the band centres (BIC and BIIC, once the continuum has been removed), and the BAR following the procedures summarized in Reddy et al. (2015) and references therein. This method was mainly developed to study main belt asteroids, and so, we have to apply a temperature correction to account for the higher surface temperature of a near-Earth asteroid. We computed the temperature corrections for the Band II centre (ΔBIIIC) and for the BAR (ΔBAR) parameter following Sanchez et al. (2012). We derived the olivine/pyroxene ratio (Ol/OI + Px), and the iron content

10http://smass.mit.edu/bsdemoeoclass.html
Calcium content of the pyroxene in this meteorite (meteorite Tourinnes-la-Grosse (second best match) indicates a low-
Furthermore, the chemical analysis available for the sample of L6 chondrites, mainly due to the lower position of its Band I centre,
In addition, two of the three best meteorite matches to the spectrum of 2014 JO25 correspond to L6 chondrites that present some amount
of metal, either in the form of ‘rust’ or as a small molar percentage in mixture. According to Cloutis et al. (1990) and Cloutis et al. (2015), the addition of metal in olivine/metal and pyroxene/metal mixtures produces a shift to shorter wavelengths of the position of the 1 μm absorption band.

5 CONCLUSIONS

The near-Earth asteroid 2014 JO25 close encounter in 2017 with the Earth was a good opportunity to coordinate efforts from different observatories and maximize the scientific outcome of this close approach. The brightness of the target allowed the contribution of small telescopes, taking into account the asteroid path from North to South, involving facilities from both hemispheres. Thanks to such cooperation, it has been possible to make a deep photometric analysis in order to derive some physical properties of this target. In addition, spectroscopic observations allowed to derive detailed mineralogical information on the surface of this potentially hazardous object.

After collecting 4540 photometric data grouped in 29 work sessions, we derived a rotational period for 2014 JO25 of $P_{rot} = 4.5286 ± 0.0004$ h using a Fourier periodogram analysis. From the analysis of the maximum amplitude of the asteroid light curve and its evolution with phase angle, we conclude that 2014 JO25 is not an extremely elongated object, with a maximum amplitude of 0.19 at a phase angle $\alpha = 24.3^\circ$, equal to an amplitude of 0.14 at phase angle $\alpha = 0^\circ$ (Zappala et al. 1990). Assuming a simple triaxial body model with $a > b > c$ and that the object’s rotation is about the c-axis we determine a lower limit of $a/b$ $<$ 1.11.

Although we have detected variations in the shape of the asteroid light curves (mainly photometric data drops in some sections), we discard the presence of a satellite. This conclusion is supported by radar images obtained from the Arecibo Observatory and Goldstone radar (Naidu et al. 2017), which show that 2014 JO25 is an irregular object, consisting of two components connected by a narrow neck, presenting concavities, flat regions, and boulders. Furthermore, the analysis performed on its rotation period allowed us to discard a tumbler nature for this target. We conclude that the light-curve variations are therefore caused by the complex shape of the asteroid and the rapid variations of the observing geometry during its close approach to the Earth.

From spectral observations, we derived that this object belongs to the S-complex. Best meteorite matches based on its visible and near-infrared spectrum correspond to L6 ordinary chondrites. The fact that the position of the absorption band around 1 μm is located at shorter wavelengths compared to what is found for S-type asteroids, and, in general, ordinary chondrites can be explained by a large fraction of low-calcium pyroxene (LCP), or, tentatively, by some amounts of metal.

The next encounter with the Earth of 2014 JO25 will take place in 2020 April, when the asteroid will reach an apparent visual magnitude of $m_v = 16.2$ at a distance of 0.16 au. That encounter will be another good opportunity to improve the photometric analysis. Furthermore, new data could be collected under a latitude/longitude PAB around $-1$ and 244 deg, receptivity, contributing to generate a three-dimensional model.

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