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Discovery of the binary nature of the Mars–crosser (1139) Atami *

R. Behrend[1], F. Manzini[2], A. Klotz[3,4], F. Colas[5,6], Y. Damerdji[3,4], S.J. Ostro[7], P. Antonini[8,6], E. Barbotin[6], L. Bernasconi[9,6], C. Cavadore[10], S. Charbonnel[11,6], J. Coloma[12], R. Cripa[13], F. Kugel[14], A. Leroy[15], J.M Llapasset[16], A. Oksanen[17], P. Pääkkönen[18], R. Poncy[19,6], R. Roy[20,6], and D. Starkey[21]

[1] Observatoire de Genève, CH–1290 Sauverny, Switzerland
[2] Stazione Astronomica di Sozzago, I–28060 Sozzago, Italy
[3] CESR, Obseratoire Midi-Pyrénées, CNRS-UPS, BP 4346, F–31028 Toulouse Cedex 04, France
[4] Observatoire de Haute Provence, F–04870 Saint Michel l'Observatoire, France
[5] IMCCE, 77 avenue Denfert–Rochereau, F–75014 Paris, France
[6] Association des Utilisateurs de Détecteurs Electroniques (A.U.D.E.), France
[7] **TBC**, USA
[8] Observatoire de Bédoin, 47 rue Guillaume Puy, F–84000 Avignon, France
[9] Observatoire des Engarouines, F–84570 Mallemort-du-Comtat, France
[10] **TBC**, France
[11] **TBC**, France
[12] Agrupación Astronómica de Sabadell, P.O. Box 50, E–08200 Sabadell, Spain
[13] **TBC**, Italy
[14] **TBC**, France
[15] **TBC**, France
[16] **TBC**, Perpignan, France
[17] Nyrölä Observatory, Jyväskylän Sirius ry, Kyllikinkatu 1, FI–40100 Jyväskylä, Finland
[18] Jakokoski Observatory, Univerity of Helsinki, P.O. Boy 14, SF–00014 Helsinki, Finland
[19] **TBC**, France
[20] Observatoire de Blauvac, F–84570 St-Estève, France
[21] DeKalb Observatory, 2507 CR 60, Auburn, IN–46706, USA

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Abstract. The minor planet (1139) Atami showed mutual eclipses features on its light curves during its 2005 opposition. Photometric and radar analysis reveal the binarity of this system composed by two bodies of the same size (7.4x4.4x4.4 km ±15%) separated by about 17.7±1.1 km. Rotations and revolutions are synchronous and the period is T=1.145±0.002 days. From a model, we derived bulk density ρ=2.2±0.5 g/cm^3. Spectrometry was performed during an eclipse. It reveals that the two bodies have the same reflectance properties (S–type). The pole orientation is also determined ($\lambda_p = 264^\circ$ and $\beta_p = +5^\circ$). These measurements suggest the formation of this binary asteroid from a huge collision of a parent body.

Key words. Planets: formation – Asteroids : binary system – Techniques: photometric

1. Introduction

Binary asteroids are composed by two bodies of almost the same sizes. Such systems are already known in the main belt (*e.g.* Merline et al. 2000), in the Trojan family (Merline et al. 2001) in the Kuiper belt (*e.g.* Veillet et al. 2002) and amongst Near Earth Asteroids (*e.g.* Pravec & Hahn 1997). In the case of Mars–crossers, only (5407) 1992AX was suspected to have a satellite of about 30% in size of the primary body (Pravec et al. 2000).

Migliorini et al. (1998) and Michel et al. (2000) studied the dynamical stability of Mars–crossers and found a median time scale of about 60 Myr. These studies concluded

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Send offprint requests to: Raoul Behrend, Raoul.Behrend@Obs.UniGe.CH

* Based on observations performed with the T1M at the Pic du Midi, TAROT at the Calern observatory, T193cm, T80cm and T120cm at the Observatoire de Haute-Provence, and by many amateur observatories coordinated by Geneva Observatory.

that Mars–crossing population should be the main intermediate reservoir of multikilometer Earth–crossing asteroids. Large number of resonnances of Mars, Jupiter and Saturn in the groups Hungaria and Phocaea and in some parts of the main belt induce chaotic diffusions that can enrich continuously the Mars–crossers population.

The orbital elements of (1139) Atami ($a = 1.947$ AU, $i = 13.1°$). are compatible with the EV (*evolved*) group amongst Mars–crossers ($1.77 < a < 2.06$ AU and $i < 15°$) defined by Michel et al. (2000). They describe this group as rather stable region (median time scale of about 100 Myr) which is enriched mainly by the Hungaria group and have exhanges with the Earth–crossing group. First photometric measurements, reported by Lupishko et al. (1988), indicated a period upper than 20 hours and a total amplitude of greater than 0.18 magnitude. The reflectance spectrum of (1139) Atami obtained on 1996 Apr. 29 by Bus & Binzel (2002b) is of S–type. Another series of spectra taken in 1997 Dec. 21-26 by Angeli & Lazzaro (2002) is of C–type. These discrepencies were noticed but not explained by the authors.

This paper is devoted to the discovery of the binary nature of the Mars–crosser (1139) Atami. We explain the observational method to detect this binary asteroid and to measure its parameters (dimension and orientation). We recorded spectra when the system is eclipsed and analyzed the surface differences of the two bodies. We suggest this double body is the result of gravitational reaccumulation of a fragments from a parent body destroyed by a huge collision as described in Michel et al. (2001).

2. Observations and processing

Techniques for detection of binarity from light curves is fully described in Behrend et al. (2005). Our strategy consists to perform photometry continuously during few hours on many asteroids. This follow-up is done by a group of amateurs of astronomy supervised by R. Behrend. Telescopes used have diameters in the range of 20 to 60 cm. In spite of their small apertures, these telescopes are well adapted to obtain 0.05 mag. dispersion for minor planets brightest than $R = 14$. Observers process their own images and extract the differential magnitudes of asteroids. Then, data are merged and analysed at Geneva Observatory (for details see Behrend et al. 2005). When the orbital plane of a binary asteroid in seen edge–on from Earth, the light curve exhibits two components: the rotational light curve and the eclipsing light curve. The first component is usually quasi-sinusoidal with an amplitude Δm. The second component is flat outside eclipses, and shows V-shape features of duration $\Delta\phi$ and depths of Δe magnitude. We reported the light curve of (1139) Atami in Fig. 1 and the corresponding extracted values in Table 1. We noticed dramatic changes during 2005 Sept. month: eclipses have completly vanished at the end of the month.

We used the TAROT telescope to measure color–indexes from filtered images. **complete the first measurements : B-V=0.92, V-R=0.51, H=12.95**. It is well compatible with B-V=+0.92 ± 0.02 published by Tedesco etal. 1989. **+ data du T120**.

Table 1. Observational parameters of (1139) Atami.

Date of radar parameters	2005-10-29.1
Inclination ψ	18°
Doppler shift $\Delta\nu$ (Hz)	17±1
Date of photometric parameters	2005-09-01.0
Phase angle φ	26°
Synodic period T (hours)	27.384 ±0.017
Rotational amplitude Δm (mag)	0.43 ±0.02
Eclipsing amplitude Δe (mag)	0.70 ±0.03
Eclipsing duration $\Delta\phi$ (phase)	0.0812 ±0.006

We used two spectrographs of the Observatoire de Haute–Provence to measure the reflectance of the surfaces of each component of the binary system. This can be done during mutual eclipses. With the T193 telescope, we used CARELEC (Lemaitre et al. 1990) in the configuration R=900 (1.8Å/pixel) in the range 4000–7600Å. Exposure times were 900s. At the T80 telescope, we used a new low resolution spectrograph in configuration R=150 (15Å/pixel) in the range 5800–7800Å. In both cases, spectra are normalized by the star SAO 53622 of spectral type G2V. Fig. 2 top shows reflectance of (1139) Atami taken on 2005 Sept. 02.072 at the phase Φ=0.95 (we defined minima of light due to eclipses at Φ=0 and Φ=0.5). This phase corresponds to the date just before the begining of the eclipse and the two bodies contribute to the spectrum. Fig. 2 bottom is the ratio of a spectrum taken at Φ=0.00 (2005 Sept. 02.126, during total eclipse) on another one taken at Φ=0.95 (just before eclipse). Variations are less than 3% between 4500 and 7500 Å. Even if the body seen at Φ=0.00 is slightly bluer, the two bodies lies in the S–type limits. T80 spectra were taken during the Φ=0.00 of 2005 Sept. 10.1 and show also an S–type.

We used the Arecibo telescope at wavelength of 12.6 cm (ν=2.38 GHz). **Technique should be completed by Steven**. The observation duration was 1.5 hour centered on 2005 Oct. 29.104. This date corresponds to exactly a phase Φ=0. We measured a double peak feature this no signal in the middle. **Figure to be done**. Each peak corresponds to the echo from a body. The separation between the two peaks is $\Delta\nu$=17±1 Hz.

3. Analysis

From spectra, we assume that the surface composition is the same for the two bodies. Some physical parameters can be extracted from the light–curve. We used a model where the two bodies are considered as prolate ellipsoids ($r_a \times r_b \times r_b$) of same size with greatest radius pointing toward each other. Their orbits are assumed to be circular of radius a and the orbital period T is synchronized on the rotational one. The densities are taken to be the same for the two bodies. The method described in Behrend et al. 2005. was modified to include radar observations. For a circular orbit inclined by an angle ψ from the line of sight, we can deduce directly the semi-major axis a when radar observations are made at ϕ=0.25 or 0.75:

$$a = \frac{c\,T\,\Delta\nu}{4\,\pi\,\nu\,\cos\psi} \tag{1}$$

From the rotational amplitude Δm, the $r_\mathrm{b}/r_\mathrm{a}$ ratio of axis for prolate ellipsoids can be calculated:

$$r_\mathrm{b}/r_\mathrm{a} = 10^{-0.4\,\Delta m} \tag{2}$$

However, this formula is valid only for occultations (*i.e.* the front body occults the back one) when the orbital plane is seen edge-on. In the case of eclipses (*i.e.* the shadow of the front body passes on the back one), we must account for the phase angle φ (Sun-planet-Earth). We denote $\Delta m'$, the equivalent of Δm for which the system seen edge-on:

$$\Delta m' = -2.5\,\log\frac{\cos\varphi}{\sqrt{10^{0.8\,\Delta m} - \sin^2\varphi}} \tag{3}$$

Now $r_\mathrm{b}/r_\mathrm{a}$ ratio verify the following formula in any case:

$$r_\mathrm{b}/r_\mathrm{a} = 10^{-0.4\,\Delta m'} \tag{4}$$

Geometrical considerations allow to link r_b to a and $\Delta\phi$ (the relative duration of one eclipse expressed in angular form):

$$r_\mathrm{b} = a\,\sin(\Delta\phi/2) \tag{5}$$

r_a is deduced from the $r_\mathrm{b}/r_\mathrm{a}$ ratio. The mass M of a body (considered as point-like, for simplicity) can be expressed via the third Kepler law:

$$M = \frac{16\,\pi^2\,a^3}{\mathrm{G}\,T^2} \tag{6}$$

where G is the gravitation constant and T the sideral revolution period. We took sideral periods equal to synodic ones because differences are not important for this study. The bulk density ρ is:

$$\rho = \frac{M}{\frac{4}{3}\,\pi\,r_\mathrm{a}\,{r_\mathrm{b}}^2} \tag{7}$$

Finally, ρ can be rewritten with only measured parameters:

$$\rho = \frac{12\,\pi}{\mathrm{G}}\,\frac{1}{T^2}\,\frac{10^{-0.4\,\Delta m'}}{\sin^3(\Delta\phi/2)} \tag{8}$$

Due to the radar observations, a, r_a, r_b are determined without any assumption about absolute magnitude nor on the albedo. In a first stage, ψ is not known. But variations of ψ induce only homotheties on the dimensions a, r_a, r_b. Even if ψ is not known, computation of the pole orientation is possible.

The rapid evolution of eclipses suggests the orbital pole is very inclined against the ecliptic plane. To confirm this, we built a model based on that described in Kaasalainen & Torppa (2001). This model simulate the reflectance of the binary system including the shadow of the front body projected on the back body. We used a Lommel-Seeliger scattering law. We scaned trying values of (λ_p, β_p) ecliptic coordinates of the orbital pole every degree on the whole directions. We obtained the beter fit of the model on observations for the solution $\lambda_p = 264\pm1°$ and $\beta_p = +5\pm5°$. Usually, light-curves do not allow to conclude on prograde or retrograde rotation, but in the begining of 2005 Sept. the phase angle φ was about 26°. This provides us the opportunity to determine the pole direction without ambiguity helped by the combination of eclipse and phase effects (Fig. 3). The pole direction known, we were able to deduce ψ=18°. Results are displayed in Table 2.

Table 2. Range values for computed parameters of (1139) Atami from the measurements.

r_a (km)	6.3 – 8.5
r_b (km)	3.9 – 5.1
a (km)	16.6 – 18.8
M (10^{13}kg)	112 – 159
ρ (g/cm^3)	1.80 – 2.70

Knowing the pole direction, we computed the (1139) Atami apparance corresponding to the date 1997 Dec. 21-26 when the spectrum shown a C–type. The southern hemisphere was face-on the Earth. In 1996 Apr. 29 and in 2005 Sept. (S–type) this was the northern hemisphere. We suggest there is a large patch of carbonaceous material centered on the south pole of the bodies. We do not know whether this patch is related to the collision history of (1139) Atami.

4. Conlusion

We revealed that (1139) Atami is a binary asteroid. Rotation and revolution are synchronous (T=27.384 hours). Bodies have comparable size (about 7.4x4.4x4.4 km ±15%) and their chemical compositions are the same with a bulk density of 2.2 g/cm^3 (±25%). Separation between the two components is estimated to be 17.7±1.1 km. We determined the pole of the orbital plane: λ_p = 264° and β_p = +5°. Fig. 4 shows the next opportunities to observe mutual events of (1139) Atami. The taxonomy is puzzling. We suggest the material is of S–type but a large area of carbonaceous materials could be deposited on the south polar region. (1139) Atami must be followed in the next oppositions to determine its true nature and should bring usefull informations to understand the role of collisions in the evolution of asteroids from the main belt to the near Earth orbits.

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References

Angeli, C.A. & Lazzaro D., 2002 A&A 391, 757

Behrend, R., Roy, R., Bernasconi, L., et al. 2005, A&A accepted

Bus, S., Binzel, R., 2002, Icarus 158, 106

Bus, S., Binzel, R., 2002, Icarus 158, 146

Kaasalainen, M. & Torppa J., 2001, Icarus 153, 24

Lemaitre, G. et al. 1990, A&A 228, 546

Lupishko, D. F., Velichko, F. P., Shevchenko, V. G. 1988 Astronomicheskii Vestnik 22, 167

Merline, W.J., Close L.M., Shelton, J.C. et al. 2000 IAUC 7503

Merline, W.J., Close L.M., Siegler, N. 2001 IAUC 7741

Migliorini A., Zappalà, V., Cellino, A. 1998 Icarus 118, 271

Michel, P., Migliorini A., Zappalà, V., 2000 Icarus 145, 332

Michel, P., Benz, W. , Tanga, P., Richardson, D.C., 2001 Science 294, 1696

Michalowski, T., Bartczak, P., Velichko, F. P., et al. 2004 A&A 423, 1159

Pravec, P., Hahn, G. 1997, Icarus 127, 431

Pravec, P., Sarounová, L., Rabinowitz, D.L. et al. 2000, Icarus 146, 190

Tedesco, E.F., J.G. Williams, D.L. Matson, G.J. Veeder, J.C. Gradie, and L.A. Lebofsky 1989, AJ 97, 580

Veillet, C., Parker, J.Wm., Griffin, I. 2002, Nature

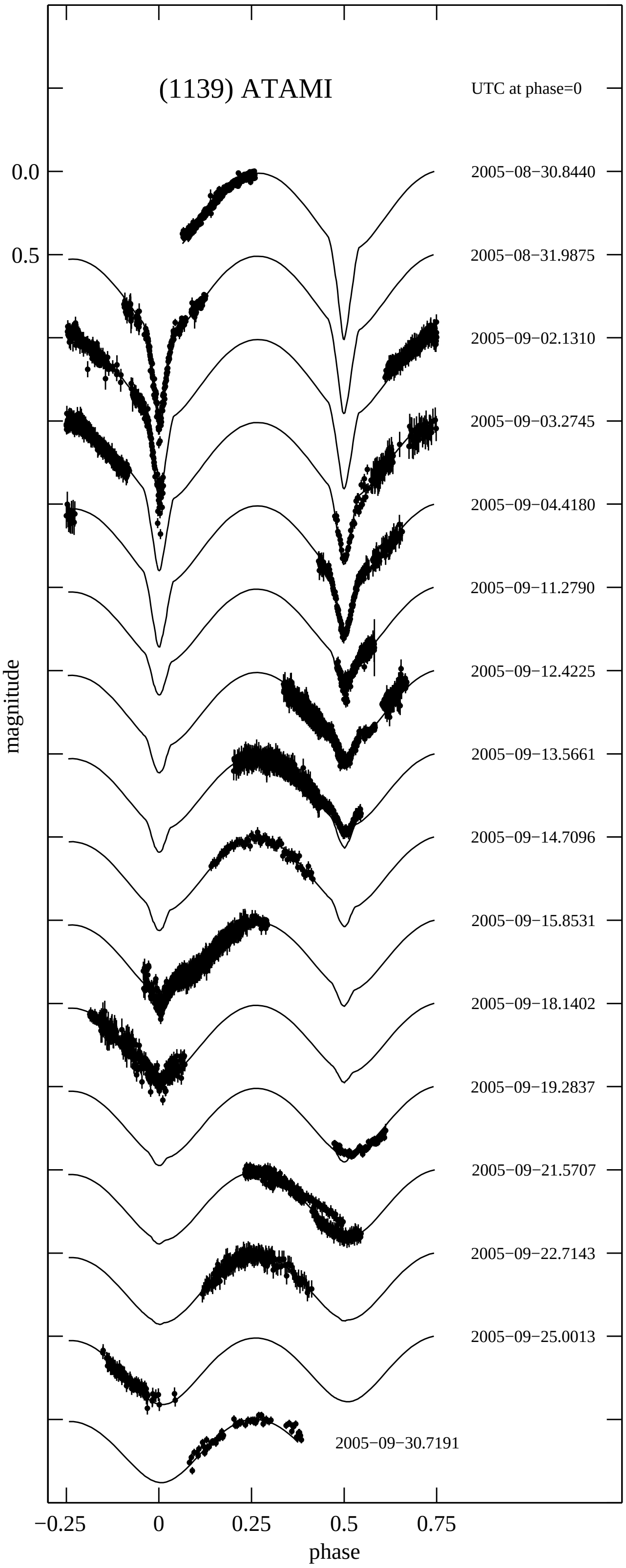

Fig. 1. Phased light curves for all observations of (1139) Atami from data of its study assuming a period of 27.384 hours. Observations are black dots. Thin curves are come from the model described in the text ($\lambda_p = 264°, \beta_p = +5°$). Each curve is shifted by 0.5 magnitude and normalized to zero mag. for the brightest part.

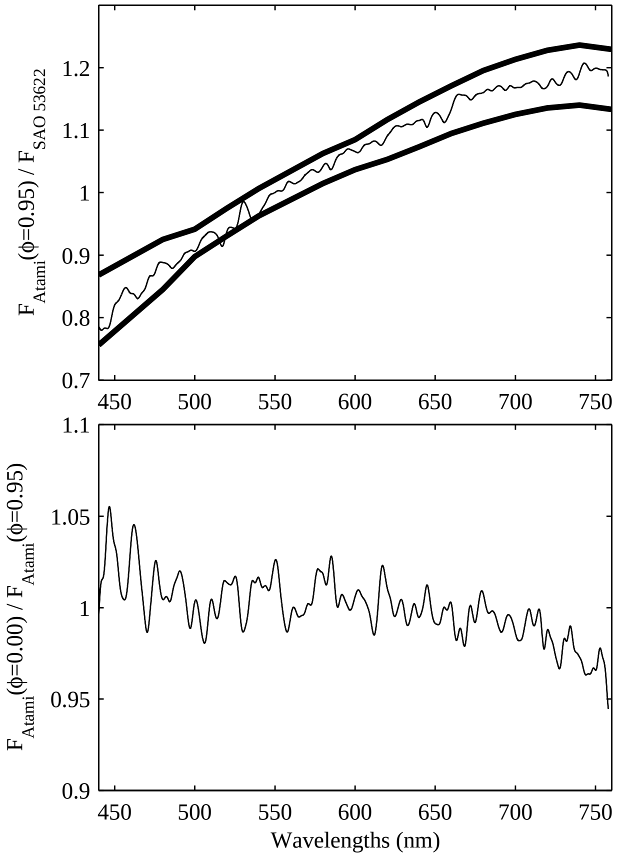

Fig. 2. Top: reflectance spectrum of (1139) Atami. Thick curves locate the limiting reflectance at 2σ for S–type asteroids from Bus & Binzel (2002a). Bottom: Ratio of the two spectra of (1139) Atami taken at phases 0.00 (total clipse) and 0.95 (just outside eclipse).

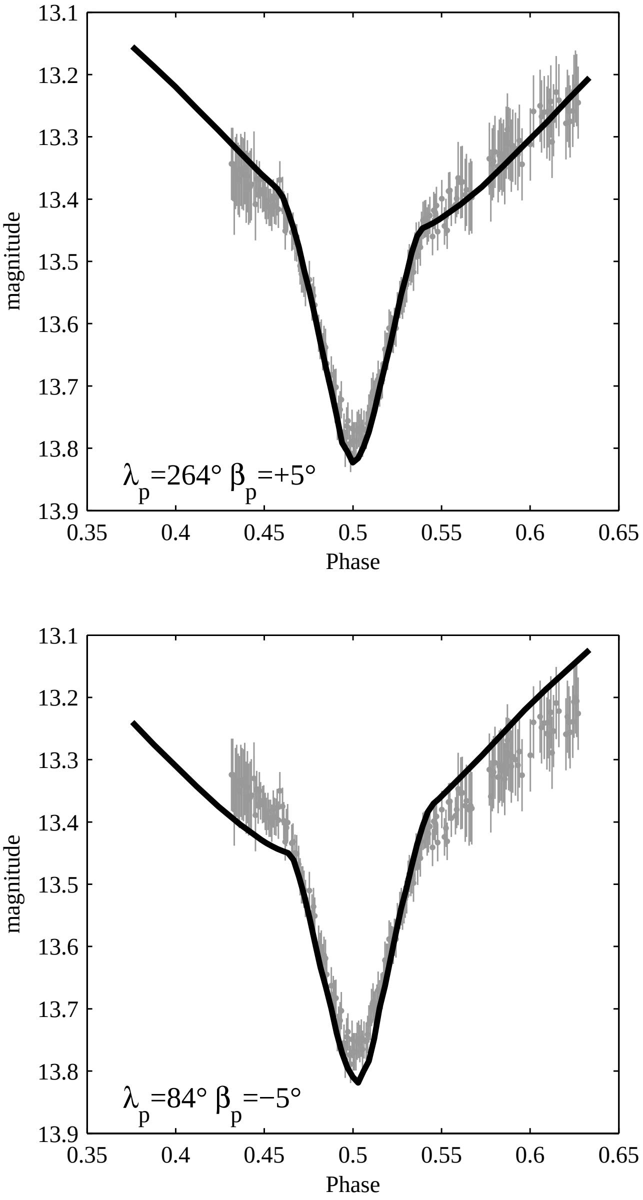

Fig. 3. Phased light curves of (1139) Atami observation (gray lines) centered on the eclipse that occured in 2005 Sept. 4.990 UT. The black lines are magnitudes computed by the model described in the text. The phase effect help to determine anambiguiously the pole direction.

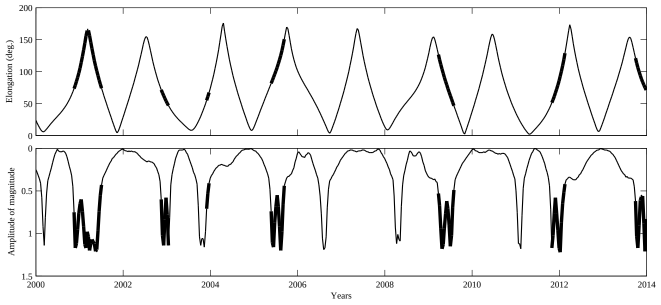

Fig. 4. Top: Elongation of (1139) Atami as seen from Earth. Bottom : Amplitude of magnitude during one period. Bold parts correspond to better windows to study mutual events of (1139) Atami (elongations upper than 50° and amplitudes upper than 0.5 magnitude).