LETTERS

Discovery of the triple asteroidal system 87 Sylvia

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After decades of speculation[1], the existence of binary asteroids has been observationally confirmed[2,3], with examples in all minor planet populations[4]. However, no triple systems have hitherto been discovered. Here we report the unambiguous detection of a triple asteroidal system in the main belt, composed of a 280-km primary (87 Sylvia) and two small moonlets orbiting at 710 and 1,360 km. We estimate their orbital elements and use them to refine the shape of the primary body. Both orbits are equatorial, circular and prograde, suggesting a common origin. Using the orbital information to estimate its mass and density, 87 Sylvia appears to have a rubble-pile structure with a porosity of 25–60 per cent. The system was most probably formed through the disruptive collision of a parent asteroid, with the new primary resulting from accretion of fragments, while the moonlets are formed from the debris, as has been predicted previously[5].

From the study of a companion's orbit, unique information about the internal properties (mass, density and porosity) of an asteroid, as well as their role in the formation of our Solar System, can be inferred. During the past two years, our group has focused on the study of main-belt asteroids already identified as binaries to carry out high accuracy astrometric follow-up and then provide ephemerides after assessing long-term dynamical effects such as precession[6–8]. Starting in August 2004 and for a period of 6 months, we initiated an observing campaign using the Adaptive Optics (AO) system and its infrared camera (NACO) available on the Very Large Telescope (VLT) at Cerro Paranal of the European Southern Observatory. Our list of 6 targets included 87 Sylvia, an X-type main-belt asteroid close to opposition (phase $<14°$) whose doubleness was discovered[9] and confirmed[10] in 2001. The primary asteroid with an angular size of ~ 0.17 arcsec is resolved in each frame. The presence of the moonlet, called S/2001(87)1, is confirmed in all frames (with a difference in brightness of magnitude $\Delta m \approx 3.8$, and maximum separation of 0.84 arcsec). We report here the detection of a second companion (called S/2004(87)1), fainter ($\Delta m \approx 4.2$) and closer (maximum separation of 0.44 arcsec) to the primary, and which is seen only at 12 epochs (Figs 1 and 2).

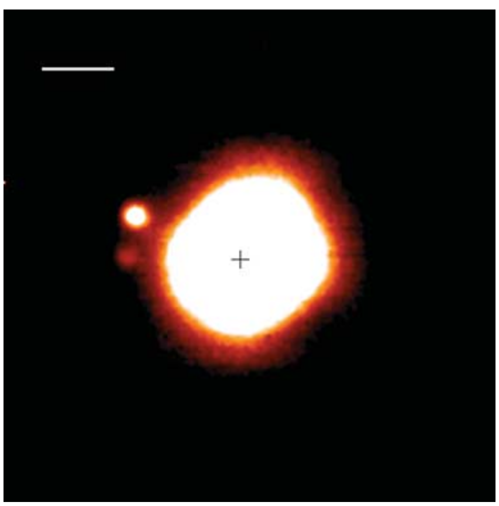

Figure 1 | One of the discovery images taken on 9 August 2004, showing 87 Sylvia and its two satellites, S/2001(87)1 and S/2004(87)1, in the K band (2.2 μm). This image is the result of shift-adding four frames with 2 s integration time reduced by standard methods. Scale bar, 0.25 arcsec. The cross indicates the position of the primary asteroid. The faintest moonlet is seen only in the frames taken under good seeing conditions (<1.0 arcsec in the visible). Twenty-seven observations were taken using the 13.3 mas per pixel scale over $\sim$2 months. AO systems, which provide in real time images close to the diffraction limit of the telescope ($\sim$0.06 arcsec at 2.2 μm), represent a very robust technique for detecting faint companions in proximity to a large asteroid and thus characterize their orbits. The peak signal-noise ratio on the main asteroid is relatively high ($\sim$2,000) because of its brightness (ephemeris predicted apparent magnitude $m_v \approx 11.5$).

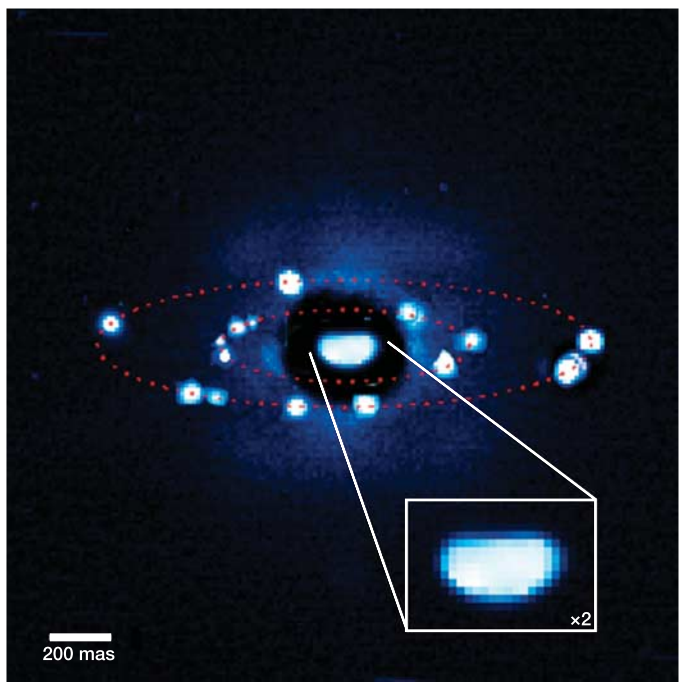

Figure 2 | Positions of S/2001(87)1 and S/2004(87)1 around 87 Sylvia. The dashed lines correspond to the moonlet orbits. This image is a composite of nine individual observations taken on nine nights and filtered with an unsharp mask (a sharpening digital process). North is up and east is left. The inset shows the shape of Sylvia's primary after applying a filtering process. The dark ring around the primary is an artefact due to the filtering. The centre of light of each moonlet is fitted by a Moffat–Gauss profile after subtraction of the residual background due to the imperfect phase correction of the AO system.

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Table 1 | Orbital elements of Sylvia's satellites S/2001(87)1 and S/2004(87)1, and physical properties of 87 Sylvia

	S/2001(87)1	S/2004(87)1
Properties of Sylvia's satellites		
Period (d)	3.6496 ± 0.0007	1.3788 ± 0.0007
Semi-major axis (km)	1,356 ± 5	706 ± 5
Eccentricity	0.001 ± 0.001	0.016 ± 0.011
Inclination w.r.t. equator (degrees)	1.7 ± 1.0	2.0 ± 1.0
Pole solution in ECJ2000 (degrees)	$\lambda = 72.4$, $\beta = 62.6$ (fixed)	$\lambda = 72.4 \pm 0.5$, $\beta = 62.6 \pm 0.5$
Inclination in J2000 (degrees)	7	7
Mean longitude at epoch (degrees)	112	63
Pericentre longitude (degrees)	14	51
Longitude of ascending node (degrees)	101	97
Physical properties of 87 Sylvia		
Mass (kg)	1.48×10^{19}	1.47×10^{19}
Density of primary* (g cm^{-3})	1.2 ± 0.1	1.2 ± 0.1
J_2	0.17 ± 0.05	0.18 ± 0.01

Both orbits, which were fitted independently (with the exception of the pole solution derived from the S/2004(87)1 orbit), give extremely consistent physical characteristics for Sylvia's primary. The epoch of reference is JD 2453249.5 UTC for S/2001(87)1 and JD 2453246.5 UTC for S/2004(87)1. λ, longitude; β, latitude; J_2, gravity field term.
*Considering the shape of Sylvia's primary to be approximated by an ellipsoid with $a = 192$ km, $b = 132$ km and $c = 116$ km, and 4% error.

Supplementary Table 1 summarizes the epoch of observations and the relative positions and brightness of each moonlet. The observations were taken over a period of time covering ~2 months, enough to obtain a good estimate of the satellite orbit. Neglecting any mutual perturbations between both moonlets, we can determine their orbit individually. We used an algorithm specially suited for the analysis of binary asteroids[11] and already successfully applied to well-constrained binary systems, such as Pluto–Charon or 121 Hermione[7,8]. Table 1 summarizes the orbital elements for each satellite. Both solutions are extremely accurate, with a residual mean square error of 10 milliarcseconds (10 mas; corresponding to 16 km). Both orbits, displayed in Fig. 3, are quasi-circular, nearly equatorial (inclination $i \approx 2°$) and prograde with respect to the spin axis orientation of the primary (which is itself prograde). The satellite S/2001(87)1 orbits around the primary at ~1,360 km, about twice the distance of the S/2004(87)1 moonlet (710 km). The period and semi-major axes of the already known moonlet are in agreement with the analysis by our colleagues based on five observations taken shortly after its discovery[12].

The angular size of both moonlets is below the VLT-NACO angular resolution. Their sizes can only be estimated by comparing their integrated brightness with that of the primary and assuming the same albedo. Our analysis showed that the relative intensities measured on the reduced frames remain constant, suggesting that they are roughly spheroidal. Their diameters are estimated as 18 ± 4 km for S/2001(87)1 and 7 ± 2 km for S/2004(87)1, assuming the same surface composition (and thus the same albedo) for the primary and the moonlets. These sizes are typical of main-belt asteroid satellites discovered so far[3,4,6–8]. However, this measurement is biased by the quality of AO systems. Smaller, and therefore fainter, moonlets

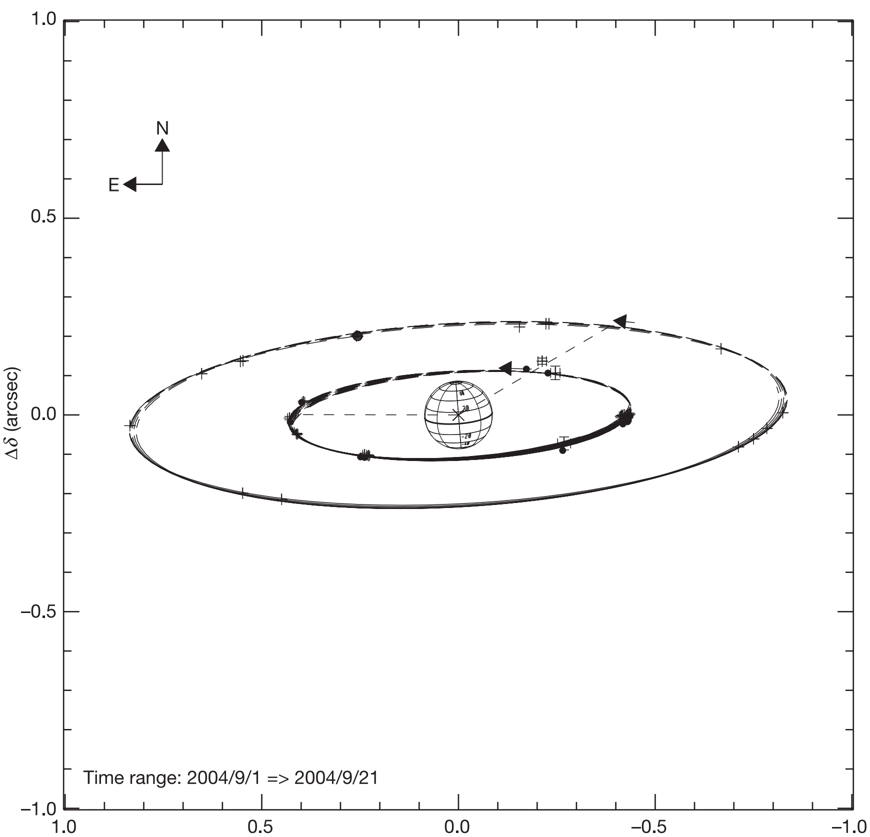

Figure 3 | The apparent orbit of Sylvia's companions projected on the plane of the sky at different epochs in September 2004. The measured positions (crosses) and their error bars (lower than 8 mas) are labelled. The primary is displayed using the pole solution of our model, and the mean diameter measured on our data set. The positions of the pericentres at their epoch of reference JD 2453249.5 UTC for S/2001(87)1 and JD 2453246.5 UTC for S/2004(87)1 are indicated (dashed lines). North is up and east is left. α, right ascension; δ, declination.

cannot be detected because of the glow of the primary produced by the residual uncorrected phase. Considering their period of revolution and neglecting the mass of the moonlets, the mass of the primary (M_{Sylvia}) is accurately derived using Kepler's third law on both moonlet orbits ($M_{\mathrm{Sylvia}} \approx (1.478 \pm 0.006) \times 10^{19}$ kg).

Since Sylvia's primary is well resolved in the AO observations, its shape can be directly estimated by fitting the image with an ellipsoid (see Supplementary Table 1). Using this technique, which was validated for other main-belt asteroids and compared with the lightcurve inversion shape[7], we can refine the size and shape of the primary. Considering the pole orientation determined by the analysis of the moonlet orbits, which is also in agreement with lightcurve inversion pole solution[13], the shape of Sylvia's primary can be approximated by an ellipsoid with axes $a = 192$ km, $b = 132$ km and $c = 116$ km (that is, $a/b = 1.46$, $b/c = 1.14$, with a mean radius Re $= 143$ km) with a 4% error, very close to the shape model derived by lightcurve inversion[13]. The averaged size is 10% larger than that determined by radiometric IRAS measurement in the far-infrared[14]. Interestingly, the second degree zonal coefficient of the gravitational potential of the primary (J_2) suggested[6] by our orbit analysis (~ 0.18) is compatible with a theoretical $J_2 = 0.14$ calculated considering the shape of Sylvia's primary and a homogeneous mass distribution. Even if the observations spanned a short period of time, the consideration of the precession effect is pertinent, especially for S/2004(87)1, since this satellite is closer to the primary and thus more sensitive to the precession effect[6,11]. Forcing $J_2 = 0$ in the orbit model for this moonlet will lead to a solution which is incompatible with the mass estimate derived from the orbit of S/2001(87)1. The results from the pole solution, the precessions of the orbits, and the mass values from both satellite orbits are highly consistent. We believe these data strongly support our discovery.

The bulk density (ρ) of the primary calculated using the mass from the orbit analyses and the size directly estimated from the AO images ($\rho = 1.2 \pm 0.1\,\mathrm{g\,cm^{-3}}$) is similar to that measured for C-type binary asteroids, such as 45 Eugenia[3,7], 121 Hermione[7,8] or 90 Antiope[3,7]. 87 Sylvia is classified, however, as an X-type asteroid[15], corresponding to an asteroid with a subtle absorption feature at 0.9 μm (tentatively interpreted as being due to the presence of orthopyroxene), adjoining both the C- and S-types. Since the composition of X-type asteroids remains unclear and their relation to mineralogical type is unknown, Sylvia's bulk porosity is not well constrained. The porosity could range from 25% up to 60%, depending on whether one considers the interior of Sylvia to be composed of hydrated carbonaceous chondrites[16] or a mixture of anhydrous silicates and water-ice. The reality might be somewhere between these two extreme values, but in all cases it is implying that 87 Sylvia's primary is made of a significant portion of void, suggesting a (loose) rubble-pile internal structure. Further analysis of X-class asteroids[17] should shed light on the actual composition of Sylvia.

Rubble-pile asteroids, as the outcomes of catastrophic collisions, are likely to be cohesionless bodies of gravitationally bound aggregates. Studies using the lightcurve inversion technique have already suggested the irregular shape of 87 Sylvia[13], implying that this asteroid may be the result of a gravitational re-accumulation process subsequent to a catastrophic collision[5]. The satellite moonlets, which revolve in a prograde manner describing quasi-equatorial and circular orbits, could be impact-captured debris. The very small eccentricity is also consistent with a well-relaxed system well damped by tidal effects. The existence of multiple moonlets formed by collisional events was suggested in several collisional simulations in which a large fragment is surrounded by a swarm of fragments[18,19], but little work has been done to study their stability over a large period of time. These moonlets (S/2001(87)1 and S/2004(87)1) orbit far enough inside the Hill sphere of the primary (1/50 and $1/100 \times r_{\mathrm{Hill}}$) to be insensitive to solar tides, but probably they are far enough from synchronous rotation with the primary (9.5 and $4.9 \times$ Re) to have stable orbits despite its ellipsoid shape[20,21]. It has been shown that the stability of Ida's moonlet[22], the first binary asteroid discovered[2], is mostly dependent on the distance to the primary; however, these authors failed to model a binary system that is stable over tens of millions of years. Our detection of the first multiple asteroidal system provides basic data that can be used to explore several long term stability scenarios for asteroidal satellites.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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