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Discovery of the Triple Asteroidal System (87) Sylvia

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These observations are based on data collected at the European Southern Observatory, Chile (73.C-0062 and 74.C-0052).

After decades of speculation[1], the existence of binary asteroids is now observationally confirmed[2,3] and several have been discovered in all minor planet populations[4]. We report here the unambiguous detection of a triple asteroid system in the main-belt, composed of a 280-km primary (87 Sylvia) and two small moonlets orbiting at 710 and 1360 km. The excellent orbital coverage provided by ~2 months of observations allowed us to estimate separately their orbital elements and refine the shape of the primary. Both orbits are equatorial, circular, and prograde suggesting a common origin. Using Kepler's third law on both orbits, the mass and density of the primary asteroid are consistent. 87 Sylvia appears to have a rubble-pile structure with a porosity of 25-60%. This triple system was most likely formed through a disruptive collision of a parent asteroid. The primary formed by accretion of fragment debris, while the moonlets are likely remnants of debris as predicted by ref. 5.

From a study of its 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 last two years, our group focused on the study of main-belt asteroids already identified as binaries to carry out high accuracy astrometric follow-up and then provide ephemeris after assessing long-term dynamical effects such as the precession[6,7,8]. Starting in Aug. 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 $<14^{o}$) whose duplicity was discovered[9] and confirmed[10] in 2001. The primary asteroid with an angular size of ~0.17 arcsec is resolved on each frame. The presence of the moonlet, called S/2001(87)1 is confirmed in all frames (Δm~3.8 and maximum separation of 0.84”). We report here the detection of a second companion (called S/2004(87)2), fainter (Δm~4.2) and closer (maximum separation of 0.44”) to the primary which is seen only at 12 epochs (Fig. 1 and Fig. 2).

Supplementary Table 1 summarizes the epoch of observations and the relative positions and brightness of each moonlet. The observations were taken on 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 on 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 rms of 10 mas (corresponding to 16 km). Both orbits, displayed in Fig. 3, are quasi-circular, nearly equatorial ($i \sim 2^{o}$) and prograde with respect to the spin axis orientation of the primary (which is itself prograde). S/2001(87)1 satellite orbits around the primary at ~1360 km, about twice the distance of S/2004(87)2 moonlet (710 km). The period and semi-major axes of the already known moonlet are in agreement with the analysis of our colleagues based on 5 observations taken shortly after its discovery[12] .

The angular size of both moonlets is below VLT-NACO angular resolution. Their sizes can only be estimated comparing their integrated brightness with the primary's one 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)2, assuming the same surface composition (thus albedo) for the primary and the moonlets. These sizes are typical of main-belt asteroid satellites discovered so far[3,4,6,7,8]. However, this measurement is biased by the quality of AO systems. Smaller, so fainter moonlets 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 is accurately derived using the third Kepler's law on both moonlet orbits ($M_{(sylvia)} \approx 1.478 \pm 0.006 \times 10^{19}$ kg).

Since Sylvia's primary is well resolved on the AO observations, hence its shape can be directly estimated fitting the image by an ellipsoid (see Supplementary Table 1). Using this technique, which was validated for other main-belt asteroids and compared with 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 primary can be approximated considering an ellipsoid with a=192 km, b=132 km, and c=116 km (i.e. a/b = 1.46, b/c=1.14 with 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 the one determined by radiometric IRAS measurement in the far-IR[14]. Interestingly, the 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)2, since this satellite is closer to the primary and then more sensitive to the precession effect[6,11]. Forcing a J_2=0 in the orbit model for this moonlet will lead to a solution which is incompatible with the mass estimate derived from S/2001(87)1 orbit. 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 of the primary calculated using the mass from the orbit analyses and the size directly estimated on the AO images (ρ=1.2±0.1 g cm^{-3}) is similar to the measured one 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 m (tentatively interpreted as due to the presence of ortho-pyroxene), 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 is ranging from 25% up to 60% whether one consider Sylvia is composed of hydrated carbonaceous chondrites[16] or a mixture of anhydrous silicates and water-ice in its interior. The reality might be somewhere between this 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 outcome of catastrophic collisions, are likely to be cohesionless bodies of gravitationally bound aggregates. By lightcurve inversion technique the irregular shape of 87 Sylvia was already suggested[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 into 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)2) orbit far enough inside the Hill sphere of the primary (1/50 and 1/100 x r_{Hill}) to be insensitive to solar tides, but probably they are far enough from synchronous rotation with the primary (9.5 and 4.9 x Re) to have a stable orbit 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 dependant of the distance to the primary. However, the authors failed to create 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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Table 1: Orbital elements of Sylvia's satellites S/2001(87)1 and S/2004(87)2.

	S/2001(87)1	S/2004(87)2
Period (days)	3.6496± 0.0007	1.3788 ± 0.0007
Semi-major axis (km)	1356 ± 5	706 ± 5
Eccentricity	0.001 ± 0.001	0.016 ± 0.011
Inclination (w.r.t. equator in degrees)	1.7 ± 1.0	2.0 ± 1.0
Pole Solution in ECJ2000 and degrees	λ= 72.4 β=62.6 (fixed)	λ= 72.4±0.5 β=62.6±0.5
Inclination in J2000 (degree)	7	7
Mean Longitude at epoch (degrees)	112	63
Pericenter longitude (degrees)	13.9	51.4
Longitude of ascending node (degrees)	101	97
Physical Properties of 87 Sylvia		
Mass	1.48 x 10^{19} kg	1.47 x 10^{19} kg
Density of Primary[1]	1.2 ± 0.1 g.cm^{-3}	1.2± 0.1 g.cm^{-3}
J_2	0.17±0.05	0.18±0.01

1. considering that Sylvia primary shape is approximated by an ellipsoid with a=192 km, b = 132 km, and c = 116 km and 4% error.

Both orbits which were fitted independently (to the exception of the pole solution derived from the S/2004(87)2 orbit) give an extremely consistent physical characteristics for Sylvia primary.

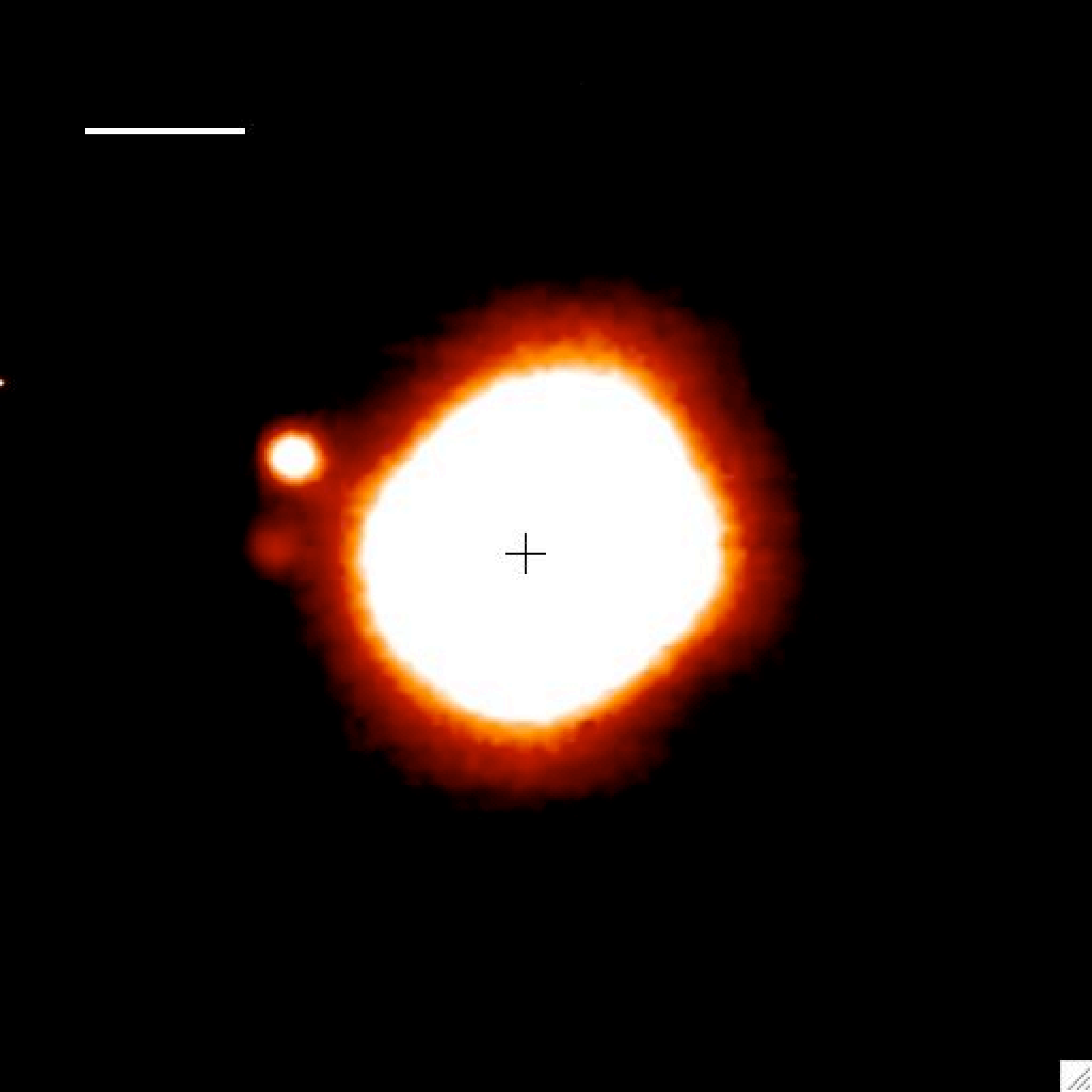
The epoch of reference is JD 2453249.5 UTC for S/2001(87)1 and JD 2453246.5 UTC for S/2004(87)2.

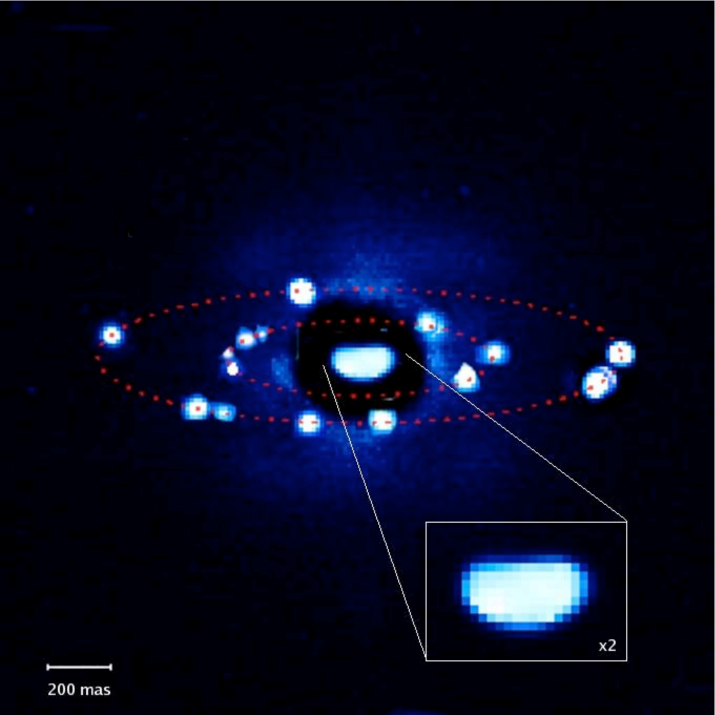
Figure 1. One of the discovery images taken August 9, 2004 showing 87 Sylvia, its two satellites S/2001(87)1 and S/2004(87)2 in K band (2.2   m). This image is resultant of 4 shift-adding frames with 2s integration time reduced by standard methods. The scale bar represents 0.25 arcsec. The cross indicates the position of the primary asteroid. The faintest moonlet is seen only on the frames taken under good seeing conditions (<1.0 arcsec in visible). Twenty-seven observations were taken using the 13.3 milli-arcsec (mas) pixel scale over ~2 months. AO systems, which provide in real time images close to the diffraction limit of the telescope (~0.06 arcsec at 2.2   m), are a very robust technique to detect faint companions in proximity of a large asteroid and thus, characterize its orbits. The peak SNR on the main asteroid is relatively high (~2000) because of its brightness (ephemeris predicted mv~11.5).

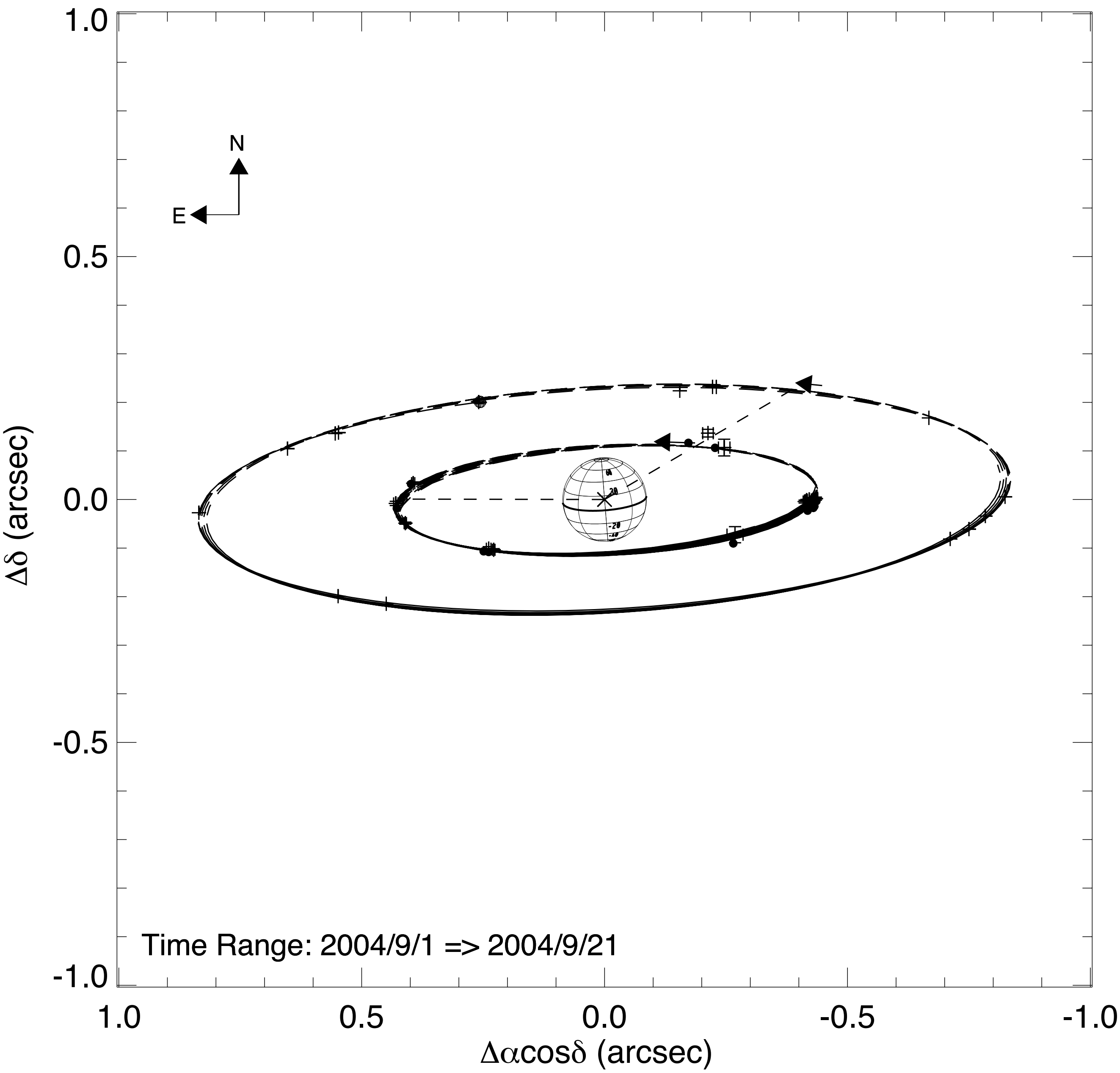
Figure 2. Positions of S/2001(87)1 and S/2004(87)2 around 87 Sylvia. The dashed lines correspond to the moonlet orbits. This image is a composite of 9 individual observations taken on 9 nights and filtered with an unsharp mask. North is up and East is left. The inset shows Sylvia’s primary shape after applying a filtering process. The dark ring around the primary is an artifact 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.

Figure 3. The apparent orbit of Sylvia's companions projected in the plane-of-sky at different epochs in September 2004. The primary is displayed using the pole solution of our model, and the mean diameter measured on our dataset. The positions of the pericenters at their epoch of reference JD 2453249.5 UTC for S/2001(87)1 and JD 2453246.5 UTC for S/2004(87)2 are indicated (dashed lines). North is up and East is left.




x2
200 mas



N
E
Time Range: 2004/9/1 => 2004/9/21
1.0
0.5
0.0
-0.5
-1.0
Δδ (arcsec)
Δαcosδ (arcsec)