Energetic ion and electron beams can induce recrystallization of amorphous layers in semiconductors at temperatures well below those that are required for thermal annealing[20,23]. There are few laboratory studies on this process for the astrophysically more relevant silicate grains. However, observations of the effect of solar flares on the structure of interplanetary dust particles indeed show evidence for recrystallization rims, indicating that these energetic particles can trigger local crystallization of the lattice[24]. These observations underpin the importance of crystallization at low temperatures as an alternative to thermal annealing followed by radial mixing as a mechanism for the formation of crystalline silicates in circumstellar disks.

A final consideration is the chemical composition of the crystalline silicates. In all our studies, we find that these are very Mg-rich with less than 1% of Fe, Ni and Ca (refs 5, 8, and F.J.M. *et al.*, and T. Lim *et al.*, manuscripts in preparation). To explain the absorption properties of amorphous silicates, it is often assumed that they have a significant abundance of metals such as Fe, Ni and Ca (ref. 25). The difference in absorption properties is evidenced by the differences in temperature for the amorphous and crystalline silicates in, for example, NGC6302 (T. Lim *et al.*, manuscript in preparation) and AFGL4106 (ref. 26). This implies that these metals are removed during the crystallization process. Although no laboratory studies have been done for silicate grains, the process of 'impurity' removal together with low-temperature crystallization has been found in laboratory studies of semiconductors[27]. Any physical mechanism for crystallization must be able to account for these differences in chemical composition between the amorphous and crystalline silicates. It would be useful to make laboratory measurements of the effects of irradiation and local heating on the crystallization process of silicates. □

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Discovery of a moon orbiting the asteroid 45 Eugenia

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Evidence for asteroidal satellites (moons) has been sought for decades, because the relative frequency of such satellites will bear on the collisional history of the asteroid belt and the Solar System, yet only one has been detected unambiguously[1–3]. Here we report the discovery of a satellite of the asteroid 45 Eugenia, using an adaptive optics system on a ground-based telescope. The satellite has a diameter of about 13 km, and an orbital period of about 4.7 days with a separation of 1,190 km from Eugenia. Using a previously determined[4] diameter for Eugenia, we estimate that its bulk density is about 1.2 g cm^{-3}, which is similar to that of the C-type asteroid Mathilde[5,6]. This implies that Eugenia, also a low-albedo C-type asteroid, may be a rubble pile, or composed of primitive, icy materials of low bulk density.

The possibility that some asteroids have satellites has been debated since the 1970s (ref. 7), when observers reported anomalous, generally unconfirmed, 'additional' events during occultations of bright stars by asteroids, sometimes interpreted to be caused by unseen companions. Asteroidal satellites have been suspected from unusual light curves, slow rotation rates, and double impact craters on planetary surfaces. The prevalence of asteroidal satellites, inferred observationally and theoretically, has ranged from common[8], to uncommon[7], to essentially absent[9]. Stable orbits for satellites can exist, even in the presence of solar or jovian perturbations[10]. The first asteroidal satellite to be found was Ida's Dactyl, discovered during the Galileo spacecraft's 1993 fly-by[1–3]. Subsequent modelling of the catastrophic collisional formation, tidal evolution, and longevity of asteroidal satellites suggests that such satellites may be common[11,12].

Study of asteroidal satellites (or their absence) will reveal much about the processes that formed the asteroids and collections of asteroids, known as 'families', and their collisional history, which, in turn, helps us understand the formation and collisional history of the planetary system[13,14]. We will also learn about the physical structures and compositions of the primary asteroids because the presence of satellites permits determination of their masses and bulk densities (given knowledge of the asteroid's size).

Direct imaging of asteroidal satellites has been hampered by lack of adequate angular resolution to distinguish objects separated by fractions of an arcsecond and by lack of sufficient dynamic range of detectors to resolve brightness differences of many magnitudes. Our work demonstrates the tremendous power of a new technology, adaptive optics, to reduce blurring caused by the Earth's atmosphere, enabling diffraction-limited imaging using large ground-based telescopes, and opening new regimes of Solar System and astronomical science.

In 1998, we began to survey 200 asteroids for companions. Our strategy was to study those asteroids that were targets of spacecraft missions, those previously suspected of having satellites, and those that are both bright and close enough to Earth that their gravitational sphere of influence subtends a significant angle. For these observations, we used the Canada-France-Hawaii Telescope.

The satellite was discovered during our first observing night, as a faint point-source within 0.76″ of Eugenia (Fig. 1). We then switched Eugenia to a higher-than-survey priority to confirm the detection and determine orbital characteristics. On both 7 and 10 November 1998, the satellite was detected during four separate sessions. The location of each detection is shown in Fig. 2, indicating both that we can track motion within a night and that there can be no ambiguity or aliasing in our period determination. Fits to the positions and constant angular velocity of the motion both indicate a near-circular orbit. Figure 3 further enhances the satellite's visibility; it is a composite of deconvolved single frames. The provisional IAU designation for the satellite is S/1998(45)1 (ref. 15).

We can reject non-satellite explanations for our observations. No known artefact in the point-spread-function (PSF) produces a point source at different position angles and separations in deep 4-minute exposures. This object was stable in position and brightness, unlike other semi-persistent similar-appearing bright spots in the diffraction pattern. None of the PSF stars (used for calibration of the instrumental profile) had similar secondary point-sources located near the 0.5–0.8″ separations observed here. The satellite, although 6 magnitudes fainter than the primary, was at times diffraction-limited, indicating that the source of the signal was external to the telescope and optical system. The companion has been imaged in three near-infrared filters (J at 1.2 μm wavelength, H at 1.6 μm, and K′ at 2.1 μm). Background stars are easily eliminated because of their rapid motion with respect to the tracked asteroid. No matches were found with the positions of known Solar System objects.

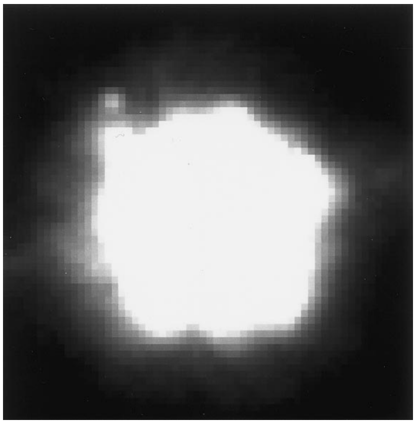

Figure 1 Discovery image, showing the asteroid 45 Eugenia and its satellite S/1998(45)1. This is a non-deconvolved summation of 16 raw images of 15-s duration each, obtained on 1 November 1998 UT. The observations were made with the 3.6-m Canada-France-Hawaii Telescope (CFHT), using the 'PUEO' adaptive optics (AO) bonette (adaptor). AO compensates atmospheric image degradation using a fast (kHz rate) deformable mirror. Unlike early AO systems developed for defence applications, PUEO is based on the concept of wave-front-curvature sensing and compensation[33] and is one of a new class of AO systems, first developed at the University of Hawaii[34]. This 19-actuator AO system requires a natural 'guide' source (star or asteroid), as faint as $V = 17$ mag, to sense the wave-front aberrations. Best results are obtained with a guide source brighter than $V = 13$ mag, in which case PUEO can deliver diffraction-limited stellar images at near-infrared wavelengths. At a wavelength of 1.65 μm, the image full-width at half-maximum (FWHM) is typically 0.12″ and has a Strehl ratio (the ratio of peak brightness of acquired image to the peak brightness of a perfectly diffraction-limited point-source) of ~0.5 (ref. 35). Images were recorded with the CFHT near-infrared camera—a 1,024 × 1,024 HgCdTe focal plane array, sensitive over 0.7–2.5 μm. The plate scale is 0.0350 ± 0.0003 arcsec per pixel, yielding a total field-of-view of 36″ × 36″. Each image set consists of four different dither positions (in a 2 × 2 14-arcsec offset pattern) on the detector. In each dither position, four 15-s images were obtained, resulting in final on-source integration time of 4 min for each final image. Each sky-subtracted, flat-fielded frame was co-aligned to within 0.01 pixels by cross-correlation of the asteroid. The 16 frames were then averaged, weighted by the peak flux in the asteroid core to produce a final image, so that frames with the least atmospheric attenuation and best AO compensation were given highest weight. In total we obtained 16 H-band (1.65 μm) averaged-images of 45 Eugenia ($V \approx 12.4$ mag) over a 10-day period (1–10 November 1998 UT); 12 of these were of high quality (AO-compensated seeing of 0.12–0.15 FWHM).

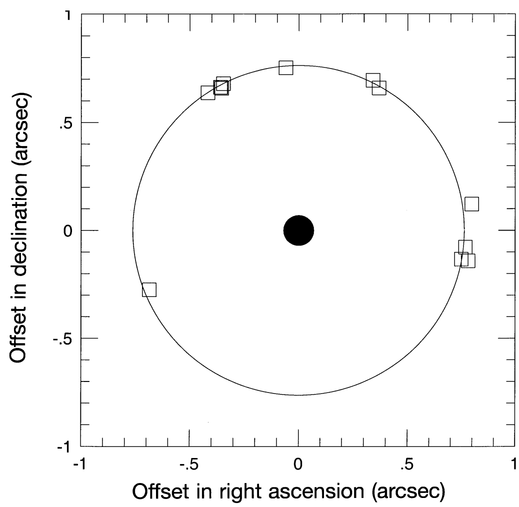

Figure 2 How the orbit of the satellite around 45 Eugenia would appear if it were observed face-on. Observations have been rotated by 34° clockwise and deprojected with respect to line-of-sight by 46°. Our orbit-pole solution is ecliptic (longitude, latitude) = (135°, − 19°), which puts the orbit close to Eugenia's equatorial plane. Clusters of points are separate detections within a single night. The central filled circle is scaled to the mean size of Eugenia.

Table 1 Properties of 45 Eugenia and targets of spacecraft fly-bys

Asteroid	Type	Albedo	Diameter (km)	Density (g cm^{-3})	Satellite?	Family member?
45 Eugenia	F (C)	0.04	215	1.2	Yes	Yes[30,31]
951 Gaspra	S	0.23	12	ND	No	Uncertain[32]
243 Ida	S	0.21	31	2.6	Yes	Yes
253 Mathilde	C	0.04	53	1.3	No	No[32]
433 Eros	S	0.27	18	2.5	No	No

ND, not determined.

Follow-up observations on 4 January 1999 UT also show the object, in a position consistent with the orbit we derive here.

As one of the 25 largest asteroids, Eugenia is well observed. It is a 'fast-rotator' with a spin period of 5.7 hours and, like other C-like asteroids, is exceedingly black (albedo 0.040; ref. 4). It is classified as an F-type (similar to C-type), with a large-amplitude light curve, implying an elongated shape, perhaps like a jacobian ellipsoid (with aspect ratios $a/b = 1.33$, $b/c = 1.65$, where a, b, c are the axes of the triaxial ellipsoid)[16], suggesting that it may have rubble-pile structure.

The satellite's orbit is inclined 46° to the line of sight. Taylor *et al.*[17] showed that Eugenia has a retrograde rotation, but with a two-position ambiguity in the pole position (that is, the direction of the spin angular momentum vector). Drummond *et al.*[16] rejected one of those two pole positions, favouring only that at ecliptic (longitude, latitude) = (127°, − 44°). Taylor *et al.* and subsequent authors agree with this pole to within 20°. If we assume that the satellite's orbit is in Eugenia's equatorial plane, then our data are entirely consistent with the pole proposed by Drummond *et al.*, but not with the second pole (286°, –26°) of Taylor *et al.* We suggest that the satellite is roughly in the equatorial plane, and that it is in a prograde orbit (same sense as primary spin), having an orbital pole within 10° of (135°, –19°). A prograde orbit is preferred for a satellite formed from impact-generated orbital debris[7,18]. A retrograde orbit, however, is more stable against perturbing effects of the non-uniform gravitational field of an oblate primary[19,20]. An orbit with an opposite sense to the asteroid's orbital motion around the Sun (as is the case here) is more stable against the effects of solar tides[21]. The derived orbit for S/1998(45)1 is stable against both of these perturbations, because it is close enough to Eugenia to minimize solar tidal effects, but far enough to be unaffected by Eugenia's shape.

We find the orbital period to be 4.691 ± 0.004 days. The long-axis separation of S/1998(45)1 from Eugenia was 0.76″ (21.8 pixels) on 1 November, when it was 2.143 astronomical units (AU) from Earth, yielding a semimajor axis of 1,190 ± 30 km. The separation and period give a gravitational parameter (gravitational constant times the mass of Eugenia) GM of 0.40 km^3 s^{-2}. We adopt the mean IRAS (ref. 4) diameter of 215 ± 4 km for Eugenia, yielding a bulk density of Eugenia of 1.2 g cm^3. The formal IRAS errors would imply an error in our density estimate of <0.2 g cm^{-3}. But the IRAS error does not account for a very non-spherical Eugenia; perhaps the IRAS observations were taken when the asteroid's cross-section was larger than the mean[22]. If so, the density could be as high as 1.8 g cm^{-3}. If instead of the IRAS errors, we use the maximum deviation expected, based on the asteroid's aspect ratio, conservative error bars are $^{+0.6}_{-0.2}$ g cm^{-3}, and are dominated by the uncertainty in Eugenia's size, not in the satellite's orbital parameters. Standard ground-based techniques can readily improve knowledge of Eugenia's size. From the brightness ratio of Eugenia to its satellite (6.14 ± 0.1 mag in the H-band, including uncertainties in Eugenia's projected diameter, and assuming the same albedo for both), we estimate the diameter of S/1998(45)1 as 13 ± 3 km.

Although not yet thoroughly examined, data from the other 25 asteroids that we observed do not show such prominent evidence for satellites as Eugenia. Other searches, both ground-based[9,23] and from the Hubble Space Telescope[24], have found no satellites in the more limited parameter space they sampled. Data from close encounters of four asteroids by spacecraft—951 Gaspra[25], 243 Ida[1–3], 253 Mathilde[5,13] and 433 Eros[14,26]—reveal only one satellite. Radar imaging of asteroids show apparent contact binaries, but no small satellites. Light curves of near-Earth asteroids suggest that some may be similar-sized binary pairs[27,28]. Although our discovery of Eugenia's satellite demonstrates that Dactyl was not a fluke, there are growing indications that asteroidal satellites are not common.

Hypotheses for Dactyl's origin[12,29] generally invoke retention of fragments in a catastrophically disruptive collision, of the type believed to form asteroid families. These studies, coupled with our detection of S/1998(45)1, suggest an emerging correlation between family membership and formation of a satellite (see Table 1). Alternatively, satellites may be formed from orbiting ejecta after a non-catastrophic oblique impact[7]. Eugenia's non-spherical shape enhances the chances that ejecta will avoid re-impact, even on keplerian trajectories, and hence of establishing orbital debris that might accrete into a satellite. Weidenschilling *et al.*[7] state that such satellites would be small relative to the primary, and would be in prograde orbits close (within a few radii initially, but evolving outward) to a rapidly-spinning primary. Eugenia and

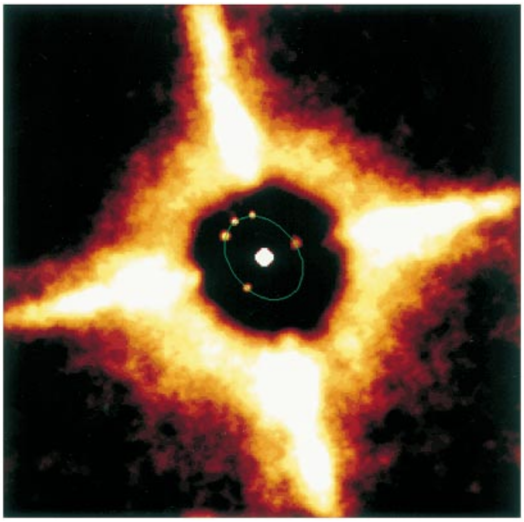

Figure 3 Orbit of the satellite around 45 Eugenia as observed. This image is a composite of individual observations taken on five separate nights (clockwise from top: 6, 7, 9, 10 and 1 November 1998 UT). North is up and east is to the left. The images are deconvolved, and the intensity of Eugenia is suppressed to enhance sharpness and clarity. The green line depicts the orbit as seen on the plane of the sky. The large, bright cross pattern results from scattering by the telescope's secondary mirror support. The variable size and brightness of the satellite reflects the variable size of the AO FWHM and is not physical.

its satellite meet these conditions. It is even possible that Eugenia's rapid spin and resulting unusual shape may be due to the collision that formed S/1998(45)1.

Our most intriguing result is Eugenia's low density. In Table 1 we compare Eugenia with other C- and S-type asteroids with directly determined densities. There may be two groupings of densities, one near 1.2 g cm^{-3} and one near 2.5 g cm^{-3}, with different associated albedos. Mathilde's low density may result from a loosely packed, porous, rubble pile of materials of rock-like intrinsic densities of ~3.5 g cm^{-3} (ref. 5). Mathilde and Eugenia are clearly structurally or compositionally distinct from the S-types Ida and Eros; but Ida may also have a rubble-pile structure[29], despite its higher density. An object as large as Eugenia would have higher internal pressures than Mathilde; it is doubtful whether such a body—made of inherently weak carbonaceous materials characteristic of its surface spectrum and albedo—could maintain the high porosity required to explain its low bulk density. Another possibility is that Mathilde, Eugenia and other C-like asteroids may be composed primarily of water ice, perhaps as remnants of burned-out comet-like bodies that have crusts of less-volatile carbonaceous material which result in their low albedos. □

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Preparing topological states of a Bose–Einstein condensate

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Observations of Bose–Einstein condensates—macroscopic populations of ultracold atoms occupying a single quantum state—in dilute alkali-metal and hydrogen gases have stimulated a great deal of research into the statistical physics of weakly interacting quantum degenerate systems[1,2]. Recent experiments offer a means of exploring fundamental low-temperature physics in a controllable manner. A current experimental goal in the study of trapped Bose gases is the observation of superfluid-like behaviour, analogous to the persistent currents seen in superfluid liquid helium which flow without observable viscosity. The 'super' properties of Bose-condensed systems occur because the macroscopic occupation of a quantized mode provides a stabilizing mechanism that inhibits decay through thermal relaxation[3]. Here we show how to selectively generate superfluid vortex modes with different angular momenta in a Bose–Einstein condensate. Our approach involves solving the time-dependent equation of motion of a two-component condensate with strongly coupled internal atomic states, as recently investigated experimentally[4,5]. The generation of vortices relies on the coupling between the states (achieved by applying an electromagnetic field), combined with mechanical rotation of the trapping potentials which confine the condensate.

Since 1995, when Bose–Einstein condensation in a dilute atomic gas was first observed[6–8], experimenters have sought a method to create a vortex in this system. In a typical experiment, around one million atoms are trapped in a magnetic harmonic potential and cooled below the critical temperature so that condensation occurs into the lowest energy quantized mode. In the usual case, this ground state has no circulation. One proposed scheme for preparing the condensate in a vortex mode[9–17] is to distort the confining potential and mechanically rotate the trap during the cooling process. In this way, the lowest energy mode may be engineered to be circulating about the axis of symmetry. Such an approach is in