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Asteroid 5535 Annefrank size, shape, and orientation: Stardust first results

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[1] The NASA Discovery Stardust spacecraft flew by the main belt asteroid 5535 Annefrank at a distance of 3100 km and a speed of 7.4 km/s in November 2002 to test the encounter sequence developed for its primary science target, the comet 81P/Wild 2. During this testing, over 70 images of Annefrank were obtained, taken over a phase angle range from 40 to 140 deg. This viewing showed that Annefrank was at least 6.6 × 5.0 × 3.4 km in size (diameters), with its shortest dimension normal to its orbit plane. Annefrank is highly angular, with flat appearing surfaces, possibly planes formed when it was fractured off of a larger parent body. For the limited part of the surface seen, Annefrank resembles a triangular prism for the main body, with smaller, rounder bodies, possibly accreted through contact. *INDEX TERMS:* 6205 Planetology: Solar System Objects: Asteroids and meteoroids; 1227 Geodesy and Gravity: Planetary geodesy and gravity (5420, 5714, 6019); 1224 Geodesy and Gravity: Photogrammetry; 6035 Planetology: Comets and Small Bodies: Orbital and rotational dynamics; 6061 Planetology: Comets and Small Bodies: Remote sensing; *KEYWORDS:* asteroid, Annefrank, Annefrank size, Annefrank orientation, NASA Stardust mission

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1. Annefrank Characterization

[2] Until the last few decades, the primary research on asteroids was pursued using Earth-based observations [*Gehrels*, 1979]. During the last two decades, interplanetary spacecraft have begun to encounter asteroids and provide much higher spatial resolution observations [*Benzil et al.*, 1989; *Bottke et al.*, 2003]. Excellent results have been obtained for determining the sizes, shapes, and orientations of Gaspra [*Belton et al.*, 1992; *Davies et al.*, 1994; *Thomas et al.*, 1994], Ida [*Thomas et al.*, 1996], Mathilde [*Thomas et al.*, 1999], and Eros [*Cheng et al.*, 2002; *Miller et al.*, 2002; *Thomas et al.*, 2002]. Additionally, advances in planetary radar have enabled Doppler-ranging observations of near-Earth asteroids [*Ostro et al.*, 2003]. Typically, the asteroids observed by spacecraft and radar have been highly irregularly shaped (very lumpy); however, there were no indications of that they may have been rubble piles, accreted through contact.

[3] On 2 November 2002 (UTC), the NASA Discovery Stardust spacecraft added yet another asteroid encountered by a spacecraft. Stardust flew by the main belt asteroid 5535 Annefrank at 3,100 km at a speed of 7.4 km/s as planned. Annefrank is a main belt, S-class asteroid (P. Weissman et al., Double spectrograph observations of Annefrank on the Palomar 200″ Hale Telescope, 17 March 2001, unpublished data, 2002; R. Benzil, personal communication, 2002) having a period of 3.29 years, a semimajor axis of 2.212 AU, an eccentricity of 0.0643, and an inclination of 4.25 deg (NASA Goddard Space Flight Center Asteroid Fact Sheet, http://nssdc.gsfc.nasa.gov/planetary/factsheet/asteroidfact.html).

[4] The flyby was used by the flight team to practice the encounter operations that will be implemented in January 2004 when the primary science target, 81P/Wild 2, will be encountered. The 3,100 km flyby was chosen, instead of the 300 km flyby planned at comet 81P/Wild 2, because of spacecraft safety considerations and to insure that Annefrank would be imaged within the pointing uncertainty due to asteroid ephemeris errors. This strategy was completely successful. *Yen and Hirst* [1997] and

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Brownlee et al. [2003] give descriptions of the Stardust mission.

[5] Over 70 broadband visual images were taken within a 15 minute flyby period, starting at a phase angle of 140 deg and ending at 40 deg while the spacecraft motion traversed 100 deg of central angle relative to Annefrank. This meant that less than 40% of the entire surface was seen, significantly limiting the size and shape determination. The image period was too short to detect rotation and spin axis direction.

[6] The camera [*Newburn et al.*, 2003a] was built using spare flight parts from previous planetary cameras to reduce costs for this NASA Discovery Program mission. These spare parts included a Cassini CCD, a Voyager 200 mm optics with filter wheel and shutter, Deep Space 1 MICAS camera electronics, etc. The camera has an angular instantaneous field of view of 59.3 μrad/pixel and at 3100 km, these images were small, only tens of pixels across (185 m/pixel at best). Even with these shortcomings, the images showed Annefrank to be highly irregular in shape, as expected for any small planetary body whose shape is not controlled by internal gravity and rotation, and where the body may be a fragment of a larger body, the accretion of planetessimals or both. Indeed, Annefrank gives the appearance of a contact binary.

[7] The overall impression is that Annefrank is highly angular, likened to a triangular prism, with a pointed end at the longest axis. A few rounded bodies appear to be in contact with the base of the prism. A few craters at the 0.5 km level are seen and surface brightness variations appear to follow the highly irregular topography rather than being dominated by albedo variations. There is a dark line running approximately north-south, possibly the contact area of the main body (prism shaped) and the smaller, rounded bodies. This could be a linear albedo feature, but more likely is a region of surface slope discontinuity, such as a contact boundary, because there is increased brightness of the smaller part, even though the phase angle is increasing. Other analyses of these images [*Newburn et al.*, 2003b] found Annefrank to be a dark object with a geometric albedo value between 0.18–0.24.

[8] Even though Annefrank is polygonal in shape, a simple ellipsoid model was used to bound its size for this preliminary, quick look results. The ellipsoid model was mapped from inertial space to image space accounting for the camera pointing and geometric properties, the perspective views and the solar illuminations. There is a wide latitude in determining size because of the limited viewing of the entire surface, combinations of large topography variations from a sphere and possible the contact bodies with the main body. Again, the surface coverage was less than 40%, and was at low spatial resolution (185–300 m/pixel). Additionally, scattered light within the optics [*Newburn et al.*, 2003a, 2003b] blurred surface detail, including the potential contact boundary. For this preliminary analysis, the smallest ellipsoid possible was determined that included most of the surface on the illuminated side of the terminator and with two positive "bumps" sticking out near and beyond the terminator of the model. These bumps may represent fragments that are not part of the main body but are now in stable contact.

[9] Figure 1 shows 12 of the encounter images spanning a range in phase angle from 120 to 40 deg where the spatial resolution varies from 300 to 185 m/pixel. To the right of each image is a simulated image based on the ellipsoidal model with two "bumps." A latitude/longitude grid is superimposed with a separation of 45 deg in longitude and 30 deg in latitude. The larger of these images are about 25×35 pixels in size. The images have been expanded by a factor of 6 with the sawtooth edges reflecting this expansion, an artifact of image processing that does not reflect any physical property of the surface. The stray light blurred the edge of Annefrank over 6 pixels. Most of the scattered light background was removed, but traces are still seen at the top and bottom edges.

[10] A fit of the ellipsoidal model to these images gave the following results:

[11] • The radii of the ellipsoidal model were $3.3 \times 2.5 \times 1.7$ km with uncertainties of $1.0 \times 0.5 \times 0.2$ km, giving a ratio of ~2 between the longest and the shortest dimensions.

[12] • The shortest axis, possibly the spin axis, was within 7 deg of being normal to the orbit plane, with an uncertainty of the same magnitude.

[13] • The first image in the upper left of Figure 1 was taken along the longest axis while the last image in the lower right was taken within 10 deg of the intermediate axis. The images used in Figure 2 include the best or highest resolution images. The longest axis is within 10 deg of the image plane in the last image.

[14] • Annefrank varies significantly (tens of % of the local radius) from the simple ellipsoidal model.

[15] Rotation about the largest moment of inertia (usually the shortest axis) is a dynamically stable orientation for a small body orbiting near its primary body that controls its motion and that has not had a large impact for millions of years [*Peale*, 1977]. Whether Stardust observed Annefrank in a stable rotation normal to its orbit plane or if this was just coincidental at the time of flyby could not be determined during the short observation time. Earth-based photometric observations of Annefrank suggest a rotation period longer than 16 hours (Weissman et al., unpublished data, 2002); therefore Annefrank would have only rotated a few deg during the flyby, below the resolution of the imaging data.

[16] Even though the use of an ellipsoid gives some insight into the size, shape and orientation of Annefrank, it points out that the actual shape is far more intricate. The ellipsoid does not match the linear appearances of the top and bottom limbs that converge to a pointed end. The terminator area appears to be a linear surface, the blunt end of a primary body, with contact planetessimals sticking out beyond this end and into the sun.

2. Conclusions

[17] Annefrank was found to be highly irregular in size and shape. The images were taken over too short of a time period to determine rotation rate, spin axis direction or see the entire surface illuminated. Topography variations dominate surface brightness. Annefrank gives the appearance a contact binary; however there can be other explanations that need to be explored in much more depth than performed in this preliminary analysis. Scattered light within the optics tended to blur the potential points of contact, making dark

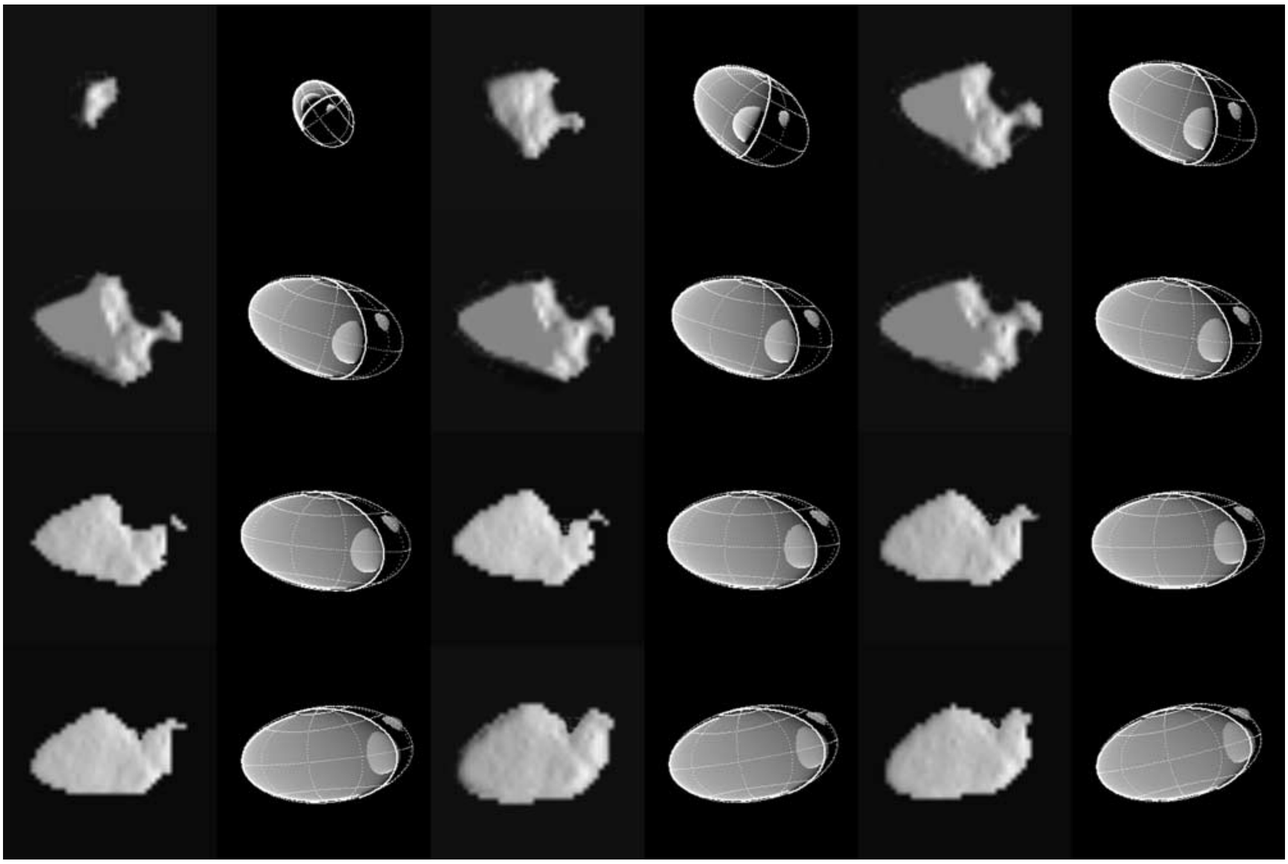

Figure 1. The model of Annefrank's size, shape, and orientation are shown to the right of 12 images (N0401AE01, N0420AE01, N0429AE01, N0434AE01, N0439AE01, N0444AE01, N0449AE01, N0454AE01, N0459AE01, N0464AE01, N0469AE01, N0474AE01). The model is based on a triaxial ellipsoid with two bumps added near the terminator. Latitude grids at 30 deg spacing and longitude grids at 45 deg spacing are overlain on the model. The optical path includes a mirror which places north near the top of the images but flipped the images such that east longitude increases to the left. The mirror is used to track Annefrank during flyby with the rotation of the mirror also inducing a rotation of Annefrank in the images. Image artifacts include a sawtooth pattern around the edges due to replicating pixels by a factor of 6 to increase image size, a rectangular notch on the right side due to the lower limit selected for stretching the image brightness and scattered light off of the limbs that was not totally suppressed by image stretch limits. Images N0429AE01, N0434AE01, N0439AE01 and N0444AE01 were saturated on the left side, which became dark after high pass filtering. Only the surface features near the terminator (on the right side) of these saturated images are visible.

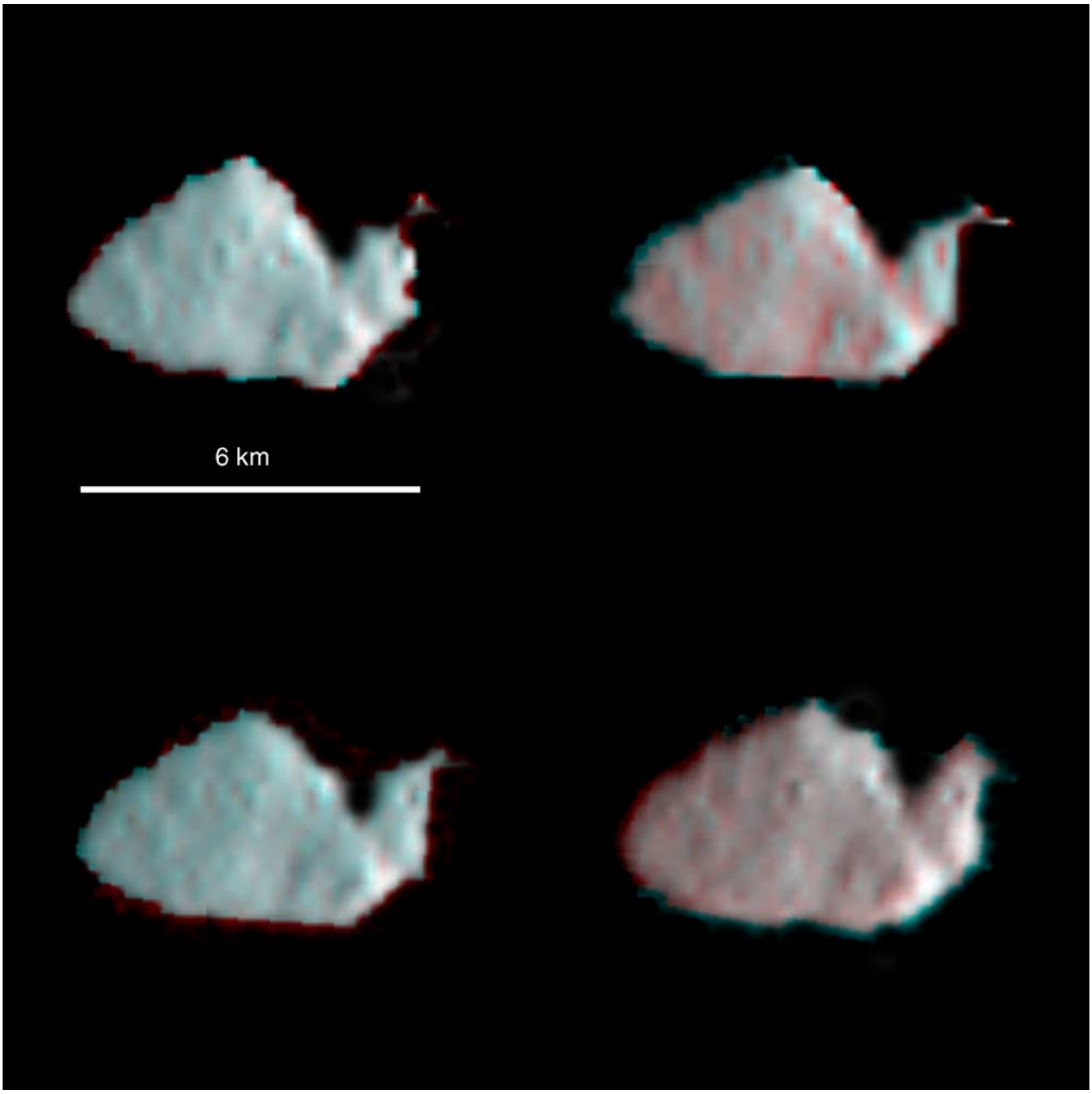

Figure 2. Combinations of images N0454AE01, N0459AE01, N0464AE01, N0469AE01, and N0474AE01 were used to produce the color stereo images. In the picture identifier, N indicates the Navigation Camera as the source of the data, 0454 indicates the picture number accumulated since launch, AE indicates the Annefrank encounter mission phase, and 01 indicates version 1 of the image.

features such as voids or gaps much brighter than in actuality. Possibly Annefrank represents a significant fraction of asteroids that are fragments of larger bodies and have accreted smaller bodies through contact, even fragments of itself ejected during impacts and re-accreted at low speed. Even though the spatial resolution of these images was low and reduced even further by scattered light, such images provide a glimpse into a heretofore unresolved asteroid and add to the growing knowledge of small bodies.

[18] **Acknowledgments.** The images used in this article were the result of the dedicated Stardust flight team at Lockheed Martin Astronautics and at the Jet Propulsion Laboratory. The Annefrank flyby was not part of the originally approved mission, but was added as a risk reduction test for the P/Wild 2 encounter. Dr. R Kirk, USGS, provided useful guidance in producing color stereo images and two reviewers, Drs. P. Thomas and J. Veverka of Cornell University, provided invaluable comments. The analyses presented here were produced at the Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aeronautics and Space Administration and sponsored by the Discovery Program Office.

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