

Asteroid 5535 Annefrank size, shape and orientation:
STARDUST preliminary results

Thomas C. Duxbury (tduxbury@jpl.nasa.gov), Ray L. Newburn, Charles H. Acton, Eric Carranza, Timothy P. McElrath, Robert E. Ryan, Stephen P. Synnott, T. Han You, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

Donald E. Brownlee, University of Washington, Seattle, Washington. 98195

Allan, R. Cheuvront, William R. Adams, Scott L. Toro-Allen, Sandra Freund, Kevin V. Gilliland, Kelly J. Irish, Charles R. Love, J. Greg McAllister, Susan J. Mumaw, Thomas H. Oliver, David E. Perkins, Lockheed Martin Astronautics, Denver CO, 80201

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Suggested Reviewers:

Dr. Michael Belton, Belton Space Exploration Initiatives, LLC, 430 S. Randolph Way, Tucson, AZ 85716

Dr. Peter Thomas, Cornell University, 422 Space Sciences Building, Ithaca, NY, 14853-6801

Dr. Randolph Kirk, USGS, Astrogeology Branch, Flagstaff, AZ, 86001

Dr. Stanton Peale, University of California, Department of Physics, Santa Barbara, CA 93106

Dr. R. Scott Hudson, School of Electrical Engineering and Computer Sciences, Washington State University, Pullman, Washington, 99164-2752

ABSTRACT

The NASA Discovery STARDUST spacecraft flew by the main belt asteroid 5535 Annefrank 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 x 5.0 x 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, accreted through contact.

Until the last few decades, the primary research on asteroids was pursued using earth-based observations (*Asteroids*, 1979). During the last two decades, interplanetary spacecraft have begun to encounter asteroids and provide much higher spatial resolution observations (*Asteroids II*, 1989, *Asteroids III*, 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 small and highly irregularly shaped.

On 02 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 3,000 km as planned. 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 3,000 km flyby was chosen, instead of the 150 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. A description of the STARDUST mission is given by Yen and Hirst, 1997 and Brownlee, *et al.*, 2003.

Over 70 broad band 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. Also, the images were all taken within 15 minutes, too short of a time to detect rotation and spin axis direction. At 3000 km, these images were small, only 10's of pixels across. 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.

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.

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 (180 - 320 m / pixel). Additionally, scattered light within the optics (Newburn, *et al.*, this issue, Newburn, *et al.*, 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. It is believed that these bumps represent fragments that are not part of the main body but are now in stable contact.

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 180 meters /

pixel. To the right of each image is a simulated image based upon the ellipsoidal model with two "bumps". A latitude / longitude grid is superimposed over the images with a separation of 45 deg in longitude and 30 deg in latitude. The larger of these images are about 25 x 35 pixels in size. The images have been expanded by a factor of 6 with the saw tooth 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.

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

- the radii of the ellipsoidal model were 3.3 x 2.5 x 1.7 km with uncertainties of 1.0 x 0.5 x 0.2 km, giving a ratio of ≈ 2 between the longest and the shortest dimensions.
- 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;
- 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 longest axis is within 10 deg of the image plane in the last image; and
- Annefrank varies significantly (10's of % of the local radius) from the simple ellipsoidal model.

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, 1979). Whether STARDUST observed Annefrank is 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.*, 2002); therefore Annefrank would have only rotated a few deg during the flyby, below the resolution of the imaging data.

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 converges 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.

Conclusions

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. It appears Annefrank is 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 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.

Acknowledgements

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Figure Captions

Figure 1. Images N0459AE01 (red) and N0449AE01 (blue and green) are used to produce this color stereo image having a convergence angle of 15 deg. The upper left is the raw image, the upper right is a high pass filtered image, the lower left is a pixel brightness differenced image and the lower right is the ellipsoidal model.

Figure 2. 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 upon 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 images and model. The optical path include 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 saw tooth 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.

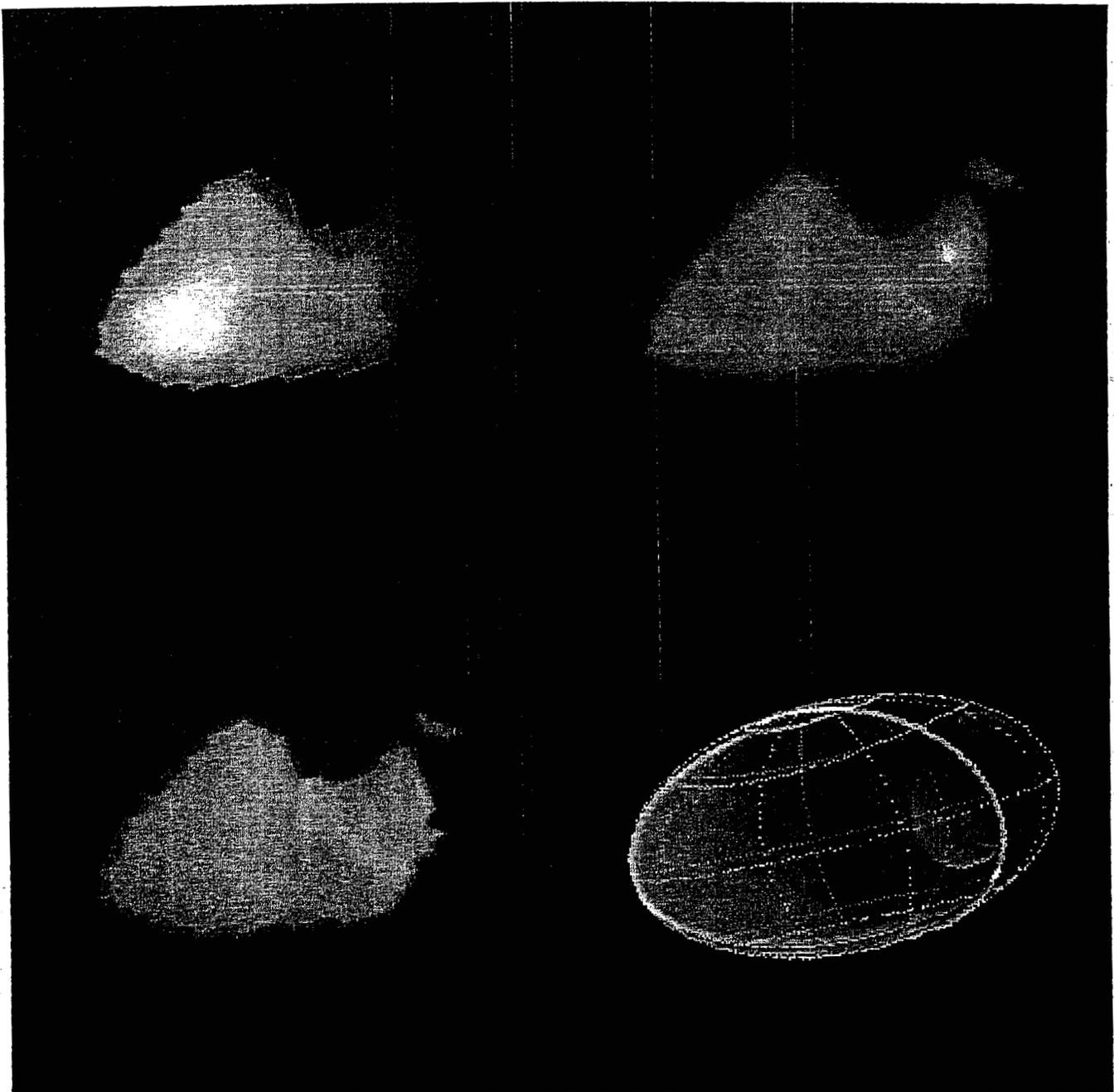


Figure 1. Stereo Image of Annefrank

