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A Close Binary Star Resolved from Occultation by 87 Sylvia

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ABSTRACT. The star BD +29 1748 was resolved to be a close binary from its occultation by the asteroid 87 Sylvia on 2006 December 18 UT. Four telescopes were used to observe this event at two sites separated by some 80 km. Two flux drops were observed at one site, whereas only one flux drop was detected at the other. From the long-term variation of Sylvia, we inferred the probable shape of the shadow during the occultation, and this in turn constrains the binary parameters: the two components of BD +29 1748 have a projected separation of 0.″097–0.″140 on the sky with a position angle 104°–110°. The asteroid was clearly resolved, with a size scale ranging from 130 to 290 km as projected onto the occultation direction, consistent with the size dimensions $385 \times 265 \times 230$ km, measured by direct adaptive optics imaging. No occultation was detected for either of the two known moonlets of 87 Sylvia.

1. INTRODUCTION

Stellar occultation provides a way to get high angular-resolution information about a celestial object. When the occulting object is well known (e.g., the lunar limb), an occultation event, when observed with fast photometry (Warner 1988), can be used to study the background object, such as to resolve a close binary (Thompson & Yeelin 2006) or to measure the stellar diameter (Ridgway et al. 1979). If the object being occulted is reasonably understood (e.g., a point star), the properties of the foreground object can be inferred, e.g., the planetary atmosphere, rings, or the size and shape of an asteroid (Elliot 1979). The occultation technique also has found applications in geodesy if the astrometry of both objects in an occultation event is well secured (e.g., Henriksen et al. 1958). In particular, a stellar occultation by an asteroid, if recorded by a group of geographically distributed observers, can yield not only the size but also the overall shape of the asteroid. For instance, the asteroid 216 Kleopatra was depicted as a long scraggly bar (Dunham et al. 1991) before its dog-bone shape was revealed with radar observations (Ostro et al. 2000). Furthermore, a 3-D model can be achieved by combining data collected from several independent occultation events of the same asteroid (Maksym 2005).

The asteroid 87 Sylvia is a large, X-type, outer main-belt asteroid with dimensions of $385 \times 265 \times 230 \pm 10$ km (Marchis et al. 2005). Its binarity was suspected early on by its light variations (Prokoféva & Demchik 1994; Kaasalainen et al. 2002), before direct imaging observations by the Keck II telescope revealed a companion (Brown 2001). Another moon was later found (Marchis et al. 2005), making Sylvia the first asteroid known to have two moonlets. Direct mass and density determinations are hence possible. Its density of 1.2 ± 0.1 gm cm^{-3} suggests a porous, "rubble-pile" internal structure (Marchis et al. 2005). The larger moon, Romulus, has a diameter of ~18 km, with an orbital distance of 1365 ± 5 km from Sylvia, whereas

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the other moon, Remus, measures 7 km across and has an orbital distance of 706 ± 5 km. It is suggested that the system was formed through a recollection of fragments from a disruptive collision.

Here we report the observation of a stellar occultation event of BD +29 1748 (SAO 80166, R.A. $= 08^{h}25^{m}01.66^{s}$, $decl. = 28°33'55.3''$, J2000.0) by 87 Sylvia on 2006 December 18. The asteroid was clearly resolved, while no occultation was detected due to either of the two moonlets. However, the background star BD+ 29 1748 was found to be a close binary. We learned (private communication, D. Herald) that up to the end of 2006, there were 24 binary discoveries including ours, among about 1000 successful observations of asteroid occultation events for which the separation and position angle of the binary components were successfully determined. Our observations, however, present an interesting case where the binary was resolved only at one site. Determination of binary parameters would have been impossible, but here we included the triaxial dimension (Marchis et al. 2005; Johnson 2005) and long-term brightness variation (Hamanowa & Hamanowa 2007; Behrend 2007) of Sylvia into consideration to constrain the size and shape of the shadow, thereby allowing an estimate of the angular separation and position angle of the binary. Section 2 describes the observations by four telescopes at two sites in central Taiwan. Section 3 presents the analysis of the light curves and derivation of the binary separation and orientation of the two stellar components in BD +29 1748. Section 4 outlines the conclusion of our study.

2. OBSERVATIONS AND DATA ANALYSIS

The shadow of the asteroid 87 Sylvia projected by BD +29 1748 was predicted to pass through central Taiwan on 2006 December 18 (Sato 2006; Preston 2006), with a ground speed of $12.14\ \mathrm{km\,s^{-1}}$. Four telescopes, three at Lulin Observatory and one in Taichung, joined to observe this event. Two of the telescopes used at Lulin are 50 cm f/1.9 TAOS telescopes (Lehner et al. 2008), each equipped with an SI-800 CCD camera, rendering a field of view of 3 square degrees. The TAOS telescopes operate in a shutterless shift-and-pause charge transfer mode to achieve a sampling rate of 5 Hz, and are designed to monitor photometry of several hundred stars simultaneously for chance occultation by Kuiper belt objects (Zhang et al. 2008). The TAOS system interrupted its routine operation to observe the predicted stellar occultation by 87 Sylvia, in an effort to detect the event with multiple telescopes and from different sites. Another telescope used at Lulin was a 40 cm f/10 telescope, equipped with an Andor U-42 CCD camera. This telescope observed the Sylvia event with regular imaging, i.e., with an exposure between the opening and closing of a shutter, with a sampling rate of approximately 2 s. In Taichung, some 80 km to the northwest of Lulin, an amateur 25 cm f/4 Schmidt-Newton telescope equipped with a Watec-902H video camera (33 ms sampling rate), with no spectral filter, was used on the rooftop of a resident building. The video images were digitized and analyzed to obtain the light curve of the occultation.

For the Sylvia event, the built-in clocks of all three telescopes at Lulin Observatory were well calibrated so the timing was recorded directly without further adjustment. For the video data taken in Taichung, however, we took frames of the onscreen clock of a calibrated computer before the event and counted the difference between the event frame and the reference frame to determine the time of the event.

Figure 1 shows the light curves taken by the TAOS telescopes. Both TAOS telescopes detected a $\Delta m = 0.42 \pm 0.07$ mag flux drop lasting for 20.4 s, which corresponds to a size scale of 247.66 km. The 40 cm telescope, located some

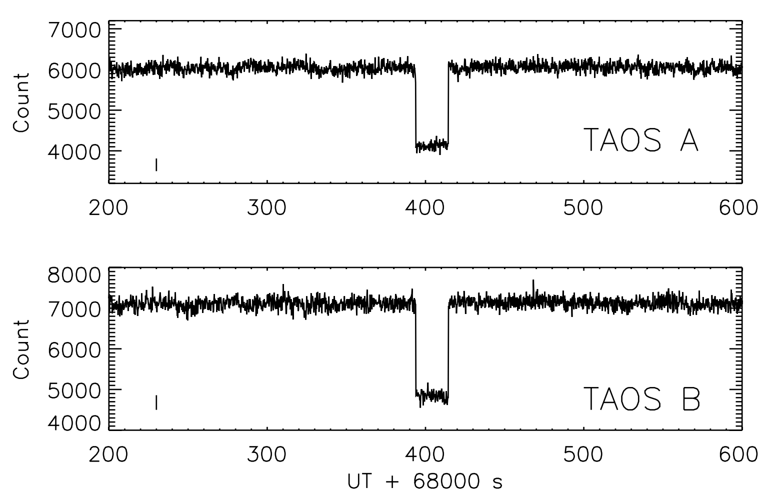

FIG. 1.—The light curves taken by the two TAOS telescopes, each with a sampling time of 0.2 s. The timing (in seconds) is referenced to the beginning of the day. The vertical bar in the lower left shows the 3 sigma fluctuation of the data away from the occultation event.

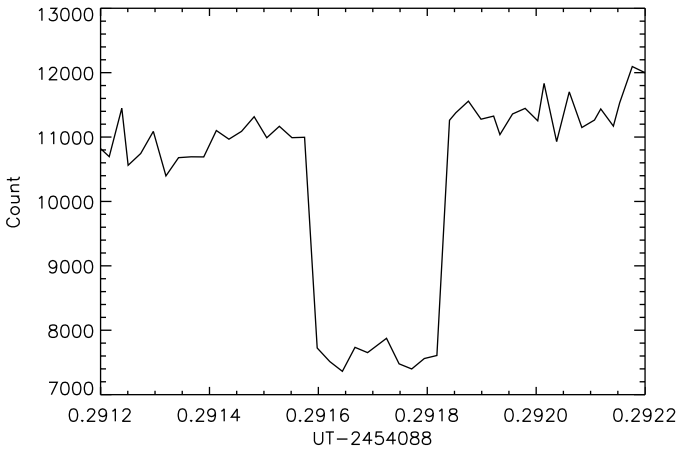

FIG. 2.—Light curve taken by the 40 cm telescope at Lulin, located adjacent to the TAOS telescopes.

20 m away from the TAOS telescopes, detected a $\Delta m = 0.39$ mag flux drop lasting for 20 s (Fig. 2), consistent with the TAOS measurements. All three telescopes at Lulin therefore must have seen the same occultation event. The slight difference between the TAOS and 40 cm results may be attributed to the different filters used; the 40 cm telescope used a standard V-band filter, whereas each TAOS system used a very broad-band (500–700 nm) filter. The flux drops, however, are inconsistent with the predicted value of $\Delta m = 2.7$ mag (Preston 2006; Sato 2006). The case is vindicated in the Taichung data, shown in Figure 3: in addition to a $\Delta m = 0.42$ mag drop lasting for 23.9 s, corresponding to 290.15 km, there was a brief reappearance, followed by a second more appreciable flux drop of $\Delta m = 0.93$ mag lasting for 10.83 s (131.45 km). The instruments used and the observational results are summarized in Tables 1 and 2.

The asteroid 87 Sylvia was clearly resolved. The duration of occultation multiplied by the shadow speed gives the size of the asteroid projected onto the occultation direction. Three such chords, ranging from 130 to 290 km, were measured in our case, all within the known triaxial dimensions of the asteroid. No occultation was detected for either of the two moonlets. Moreover, it appears that the star under occultation, BD +29 1748, is a binary, as evidenced, in addition to the combined flux drop of the two events seen in Taichung, by the lack of similar flux changes in other stars observed at the same time (Fig. 4).

The BD +29 1748 system has a spectral type of about F8 as given in the SAO catalog. The spectral type was confirmed by a spectrum taken by the 1 m telescope at Lulin a few days after the Sylvia event. The UCAC2 catalog lists an apparent magnitude of $V \sim 9.9$ mag for BD +29 1748. The flux drops for

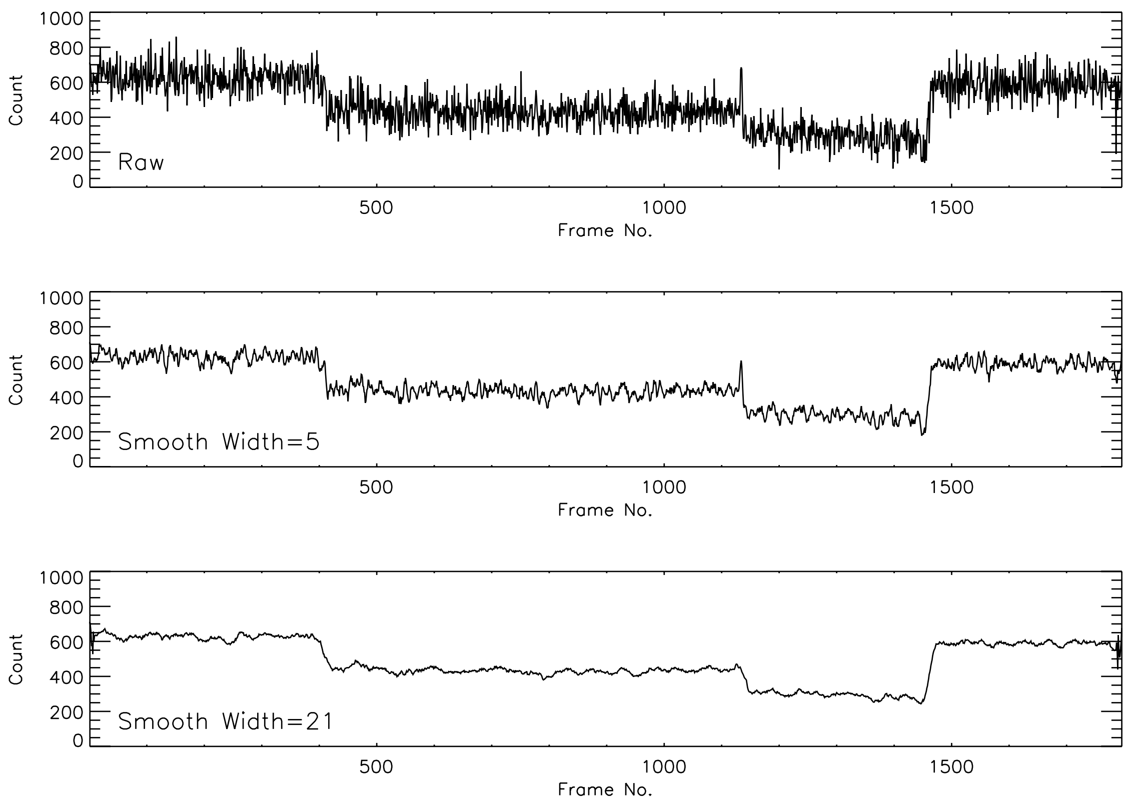

FIG. 3.—(*Top*) The light curve taken by the video camera in Taichung, with a sampling rate of 33 frames per second; (*Middle*) the same light curve smoothed by a running box-car average (equal weighting) with a width of 5 frames; (*Bottom*) the same but smoothed with a width of 21 frames.

TABLE 1
INSTRUMENT PARAMETERS

Site	Coordinates	Elevation	Telescope	Detector	Data Storage
Lulin	120°52′25″E, 23°28′07″N	2,862 m	0.5 m f/1.9	SI 800	Personal computer
Lulin	See above	See above	0.4 m f/10	U42	Personal computer
Taichung	120°39′00″E, 24°06′48″N	68 m	0.25 m f/4	Watec-902H	Digital camcorder

the two components, 0.93 and 0.41 mag, therefore lead to 10.42 mag for the primary and 10.94 mag for the secondary. If extinction is negligible, given an absolute magnitude of 4.0 for an F8 dwarf, the distance to BD +29 1748 should be ~370 pc. The secondary, if also a dwarf, then should be a G1 star. With a size of 200–300 km across, the asteroid would have an angular size of ~0″.1. In comparison, either background star has a physical size similar to that of the Sun, so would sustain an angular size of about 0.01 mas at its distance, which is much smaller than the asteroid and could not be resolved in our observations.

3. DERIVATION OF BINARY PARAMETERS

Because BD +29 1748 was resolved to be a binary pair only at one site, derivation of the binary parameters, namely the angular separation and orientation in the sky of the star components, would have been impossible. However, because the size and shape of Sylvia has been well measured, it turns out to be feasible to constrain the binary geometry with reasonable accuracy from the triaxial dimension of the asteroid and its long-term brightness variation.

We started out with the shadows of Sylvia cast by the primary (S_A) and by the companion (S_B) projected onto the surface of the Earth at the time of occultation (Fig. 5) For simplicity, we assume elliptical shadows. The constraints on the geometry of the shadow ellipses are as follows:

1. The shadow caused by the primary (S_A) is identical to that by the secondary (S_B).
2. The shadow was predicted to move with a speed of $12.14\ \mathrm{km\,s^{-1}}$ in the direction of 309.3° east of north.
3. One site (Taichung) witnessed the occultation events of both the primary and secondary, whereas the other site (Lulin) detected only the event of the secondary.
4. There are two chords through S_B, with lengths of $L_1 = 290.15$ km (observed in Taichung), and $L_2 = 247.66$ km (observed at Lulin), and one chord through S_A, $L_3 = 131.45$ km (observed in Taichung) (see Table 2.)
5. The distance between L_1 and L_2 projected onto the occultation direction is 41.3 km.

Our next step is to estimate the size and shape of the shadow ellipse. An asteroid varies its brightness based on its reflecting surface area and phase angle with respect to the Sun as the spinning asteroid orbits the Sun. Given the triaxial dimensions of $384 \times 264 \times 232$ km, Sylvia should therefore reach its maximum brightness when its projection becomes a 384×264 km ellipse. Sylvia has been measured to have a 0.215984 ± 0.000002-day period with an amplitude of 0.273 ± 0.005 mag (Hamanowa & Hamanowa 2007; Behrend 2007). Tracing back to the time of our observations, we found the asteroid's brightness to be 0.26 mag fainter than at its maximum. Thus the cross section of the asteroid facing the Earth at the time of observation should be less than 78% of the 384×264 km ellipse. There could be many possible major/minor axes combinations, but the minor axis must be between 232 km and 264 km, which in turn dictates the major axis of the shadow to be between 341 km and 300 km. The actual situation must fall between the two extreme cases, a 300×264 km ellipse and a 341×232 km ellipse.

The next step is to find a line L_4 which is parallel to L_1 and intersects S_B with a chord length of 131.45 km. This chord on S_B is to be connected to the one on S_A which represents the second occultation observed at Taichung. The upper-left end P_3 of such a chord on S_B corresponds to point P_2 on S_A. The separation and position angle between S_A and S_B, i.e., the binary parameters, can hence be readily derived. The results are demonstrated in Figure 5 for the two extreme cases, and are summarized here:

The 300×264 km Case. In the extreme case where the minor axis is 264 km, the length of the major axis should be 300 km. Note that L_1 and L_3 were both observed in Taichung,

TABLE 2
OBSERVATIONAL RESULTS

Site	Immersion (h:m:s)	Emersion (h:m:s)	Immersion (h:m:s)	Emersion (h:m:s)	Duration (s)	Flux Drop (mag)
Lulin/TAOS	18:59:54	19:00:14.4	....	....	20.4 ± 0.2	0.41
Lulin/0.4 m	18:59:53	19:00:13	....	....	20 ± 2	0.39
Taichung	18:59:57.73	19:00:21.63	....	....	23.90 ± 0.033	0.42
	....	....	19:00:21.86	19:00:32.69	10.83 ± 0.033	0.93

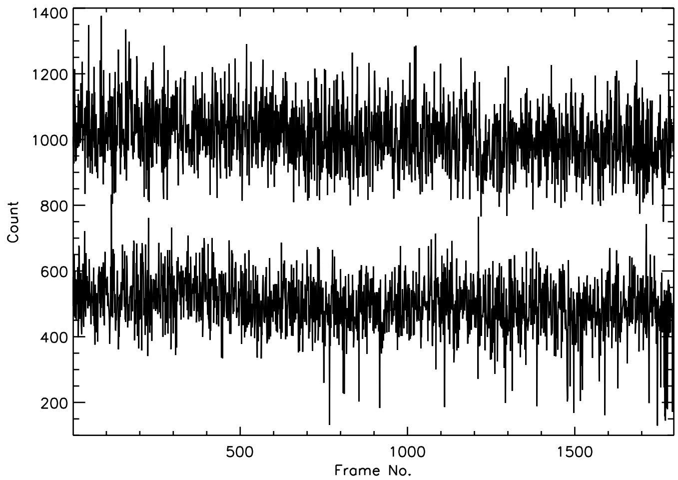

FIG. 4.—Two comparison stars in the same field of, and observed at the same time with, BD +29 1748. No flux changes similar to those detected in BD +29 1748 (see Fig. 3) were seen.

but because S_A and S_B are identical, one can find a corresponding chord on S_B. In this configuration, the angle between L_1 and north is 50.7° and the angle between L_1 and the major axis of S_B is 4.6°, so the major axis of S_B should be 46.1° west of north as demonstrated in Figure 5a. The separation between S_A and S_B is thus 227 km or, given the distance of the asteroid of 2.83016 AU at the time, 0.″110 on the sky, with the position angle of the secondary relative to the primary to be 107°.

The 341×232 km Case. When the minor axis is at its minimum, i.e., 232 km, the length of the major axis would be 341 km. Following the same calculation as for the preceding case, we obtained the angle between L_1 and the major axis of S_B to be 30.3°. So the major axis of S_B should be 20.4° west of north, as shown in Figure 5b. The separation between shadows S_A and S_B is estimated to be 198 km or 0.″97, with the position angle of the secondary relative to the primary to be 104°.

The ranges of binary parameters derived are values estimated from two extreme cases under the assumption of an elliptical shadow for 87 Sylvia. In general, the actual shape of the shadow should be more complex than a simple ellipse, with dimensions, here estimated by light variation of the asteroid, largely uncertain. The elevation of the asteroid (and hence the star) during occultation was 84°, i.e., close to zenith, so the shadow distortion due to the curvature of the Earth's surface should be negligible. But in case of Sylvia, the actual dimensions $385 \times 265 \times 230$ km are well determined by adaptive optics imaging. The measured average radius of 140 km is about 10% larger than that inferred by the *IRAS* observations (Marchis et al. 2006). The polyhedral profile can be computed, given the ecliptic coordinates of the pole and the triaxial dimensions of the asteroid.

For the pole coordinates, Magnusson (1990) inferred a prograde solution of ecliptic longitude and longitude (66°, $+67°$) or

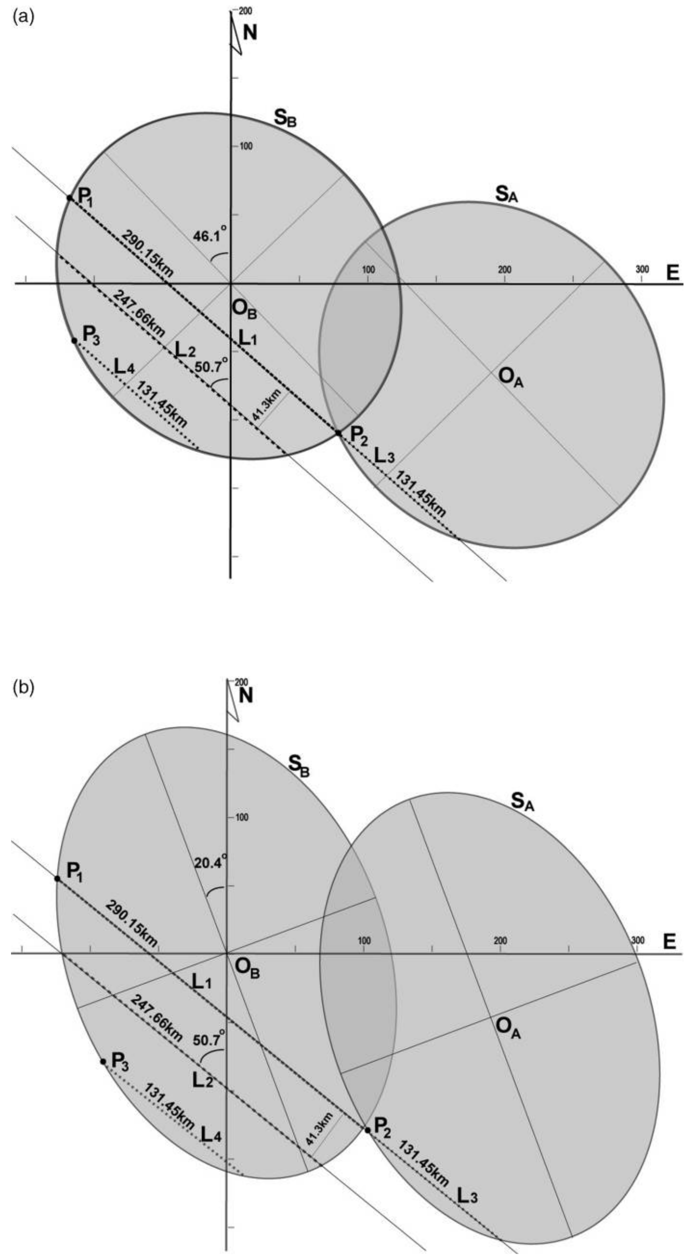

FIG. 5.—The geometry of the asteroid shadow in the two extreme cases. The orientation of the binary stars has a mirrored configuration of the shadow, i.e., with B (secondary) being to the southeast of A (primary).

(296°, $+59°$). From photometric lightcurve inversion, Kaasalainen et al. (2002) derived the pole solution (72°, $+66°$), whereas recently Kryszczyńska et al. (2007) gave (82°, $+55°$) degrees. We used the IMCCE website, http://www.imcce.fr/page.php?nav=en/ephemerides/formulaire/form_ephephys.php, which adopts the pole coordinates of (72°, +63°), to compute the profile of 87 Sylvia at the time of occultation, as shown in Figure 6. An average radius of the asteroid of neither 130 km (the *IRAS* value) nor 120 km (10% smaller) could give a satisfactory fit to the observational constraints by the occultation chords. An

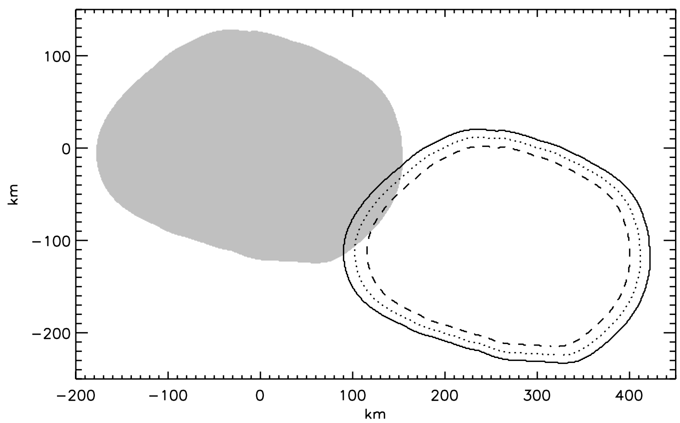

FIG. 6.—The same as Fig. 5 but inferred from the pole coordinates and the triaxial dimensions of 87 Sylvia. The top-left (northwest) shadow is for the secondary, with an average radius of 140 km. The bottom-right shadow is for the primary, marked with an average radius of 140, 130, and 120 km, respectively.

average radius of 140 km—the value measured by Marchis et al. (2005)—on the other hand, could fit the occultation observations, and the profile consistently bears resemblance to the two cases shown in Figure 5. This means the derivation of binary parameters based on the assumption of an elliptical shadow is justified. The profile is equivalent to an ellipse of 332×246 km, with the position angle of 7.4° of the semimajor axis with respect to the EW direction. With the polyhedral profile, the binary has an angular separation of 0.″140 and position angle of 110°.

Note that for each disappearance and reappearance in the light curve recorded in Taichung, which is noisy but with a fast sampling rate as seen in the smoothed light curves (Fig. 3), the signal changed more slowly than if the occultation had occurred perpendicular to the local asteroid limb. This suggests that the passage of the shadow ellipse was oriented in such a way that the contact angle—the angle relative to the normal at the contact point of the occultation (zero degrees for a "head-on" occultation, and close to $\pm 90°$ for a grazing event)—is substantially larger than 0. As seen in Figure 5, this is very likely the case, though the actual contact angle is not certain because of the unknown local shape/limb of the asteroid.

4. CONCLUSION

Occultation by the asteroid 87 Sylvia revealed that the star BD +29 1748 consists of a close pair. The primary is an F8 star with an apparent magnitude of $m_v = 10.42$, and the secondary, possibly a G1 star, has $m_v = 10.94$ mag. The projected separation between the primary and the secondary is 0.″097–0.″140, with a position angle of 104°–110°. The asteroid was clearly resolved, with projected size scales ranging from 130 to 290 km, consistent with the triaxial dimensions determined by adaptive optics imaging. No occultation was detected for either of the two known moonlets of 87 Sylvia.

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