Adaptive Optics Observations of Small Moons of Saturn [1]

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ABSTRACT

We report near-infrared observations of Prometheus and Janus taken on 9 and 13 November 2000 (UT) with the Palomar Adaptive Optics System on the 5-m Hale telescope at Palomar Observatory. Dione, Rhea and Tethys were used as guide stars for the adaptive optics system, and, though they were outside the isoplanatic patch of the region of interest, they allowed significant correction of the atmospheric distortion.

Prometheus, which is usually impossible to observe from the ground due to scattered from the A ring, was imaged at superior conjunction with Saturn. At the time of the observations, the rings of Saturn were blocked by the southern limb of the planet, while the moon passed just $0.35''$ below. A K filter, in a methane absorption band, was used to suppress light from the disk of the planet, and template subtraction removed much of the scattered light from the planet and the A ring. Prometheus was found to be $21.9 \pm 0.3°$ of mean longitude behind the position predicted by Voyager-era ephemerides, consistent with the orbital lag discovered during the 1995 ring-plane crossing.

1. Introduction

Saturn's inner moons Prometheus, Pandora, Janus and Epimetheus are challenging targets for earth-based observations. They are small and therefore faint, with mean opposition magnitudes of m_V=15.8, 16.5, 14.5 and 15.7, respectively. Janus and Epimetheus

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are in a 1:1 resonance, sharing a mean semimajor axis of 151,400 km, while Prometheus and Pandora orbit at 139,400 and 141,700 km, respectively, on either side of the narrow F ring. Their proximity to the bright A ring of Saturn, which extends out to 136,800 km, means that they are all usually lost in the glare of scattered light from the rings.

It is, however, possible to image these faint satellites when the outer edge of Saturn's main rings is covered by the disk of the planet, but the satellites just beyond the rings are not. The satellites can be imaged as they move past the apparent "gap" in the rings near Saturn's pole. Such an opportunity occurs about 5 years before and after each ring plane crossing.

In 1990, a ring opening angle between 21.4 and 23.9° made it possible for Nicholson *et al.* (1992) to observe Janus and Epimetheus as they transited $\sim$ 0.5–0.9″ above Saturn's north pole. A filters with $\lambda_0 = 2.2\ \mu$m, centered in a deep methane absorption band, strongly reduced the light from the planet, and successive images were subtracted to decrease the scattered light from the rings. The positions of the satellites were measured with an accuracy of 0.15″–0.35″, or 0.4°–0.9° of orbital longitude.

A similar geometry recurred in 2000 when the ring opening angle was between −21.4 and −23.9°, presenting another opportunity to image Janus and Epimetheus, this time as they passed under the south pole of the planet. Pandora and Prometheus, on the other hand, are much closer to Saturn's rings than are Janus and Epimetheus. Since the ring opening angle must be large enough for the moons not to be occulted as well, their observation is possible over a smaller range of ring opening angles, −23.40 to −23.89°. As they traverse the narrow "gap" where the disk of Saturn covers the A ring, Pandora and Prometheus are at most 0.35″ from the limb of the planet, compared to the $\sim$ 1″ maximum separation for Janus and Epimetheus. With the aid of adaptive optics, however, it is possible to observe Pandora and Prometheus from the ground in this geometry.

A previous opportunity to observe these 4 inner satellites arose during a different geometrical configuration, the ring-plane crossings of 1995. Saturn's rings were then seen nearly edge-on as viewed from Earth, minimizing their brightness. Janus, Epimetheus, Pandora and Prometheus were imaged using the Hubble Space Telescope in May, August and November 1995 (Bosh and Rivkin 1996; Nicholson *et al.* 1996). At this time, it was discovered that the orbits of Pandora and Prometheus had changed since the Voyager epoch. There was a lag of 19° in Prometheus' orbital position, while Pandora's mean motion had apparently decreased (McGhee *et al.* 2001).

French et al. (1998, 2000, 2001) have continued to monitor Prometheus' position in HST images using shift-and-subtract techniques to reduce scattered light from the rings.. The lag of Prometheus has continued to increase at a rate of approximately 0.6° per year. After allowing for previously-neglected perturbations due to the nearby 3:2 resonance with Mimas (Dones et al. 1999), French et al. (2001) have also shown that Pandora is now leading the corrected Voyager ephemeris by $\sim 28°$.

The origin of these unexpected orbital changes is presently unknown (see Dones et al. 1999; Showalter *et al.* 1999, for some hypotheses) , and motivated the present work. The AO observations presented here should supplement the ongoing HST observations by French and colleagues.

2. Observations

On 9 and 13 November 2000 (UT) we observed Saturn with the 5 m Hale telescope at Palomar Observatory, California. The Palomar Adaptive Optics (PALAO) system was used to correct for atmospheric seeing. The Palomar High Angular Resolution Observer (PHARO) near infrared camera, with a 1024×1024 Rockwell HAWAII HgCdTe array, was used in the 40 mas per pixel mode, with a $40'' \times 40''$ field of view. Saturn was 1.365×10^9 km from the Sun and 1.22×10^9 km from Earth. Each pixel spans 237 km at Saturn, and the field of view of 2.4×10^5 km is not quite large enough to image Saturn's entire ring system in one frame. Saturn was near opposition, with the phase angle varying from 1.2° to 0.7°. The ring opening angle was −23.7°, and it took 13 min for Pandora or Prometheus to cross the $2''$ gap in the rings (see Fig. 1). We imaged Saturn using a standard K filter ($\lambda_0 = 2.2$ μm, $\Delta\lambda = 0.4$ μm), which largely matches a deep methane band where sunlight is absorbed by the planet's atmosphere, leaving the disk of the planet exceptionally dark, particularly at polar latitudes. The integration time was 10 sec.

The PALAO wavefront sensor (WFS) requires a guide star preferably brighter than 11th magnitude in the visible and located within $\lesssim 20''$ of the region of interest (within the isoplanatic patch at 2μm.) The likelihood of Saturn being near an appropriate background star at the time of any given observation is low, but Saturn's moons Dione, Rhea and Tethys, all with $m_V \approx 10$, proved to be acceptable guide objects. With diameters $\lesssim 0.1''$, the moons appear to the WFS as unresolved point sources.

The largest obstacle in using the adaptive optics system proved to be scattered light from the rings of Saturn. The intensity of the scattered light falls off rapidly with distance from the rings, skewing the WFS camera's guide-star image centroids and making it impossible for the AO system to remain locked on the point source. The WFS images are sky-subtracted, so we attempted to correct for the scattered light by taking a WFS sky frame from a region near the rings where the orientation of the gradient was similar to that at the guide object. This proved only partially successful, and all attempts to guide on Enceladus (m_v=11.8), often the closest moon to the region of interest, failed.

It was therefore necessary to choose a satellite more distant from the rings, although that meant that the satellite was farther from the field of interest and the image quality was degraded somewhat. With the PALAO system guiding on Rhea, for example, the FWHM of Tethys, at a distance of $27''$, was 12 pixels or $0.48''$. While this offered a substantial improvement over the uncorrected image quality, it does not approach the theoretical diffraction-limited image size of $\sim 0.10''$ at 2.2μm.

Prometheus and Pandora have orbital periods of 14.712 and 15.084 h, respectively, and they both transited below the south pole of Saturn during the nights of 9, 11 and 13 November 2000 (UT), presenting three opportunities for imaging each satellite during our observing run. No observations were made on 11 November due to bad weather.

On 9 November, Dione was used as a guide object. It was to the southeast of Saturn, $22''$ from the south pole (see Fig. 1.) Our first attempt to image Pandora failed because the PALAO system could not be locked onto Dione, due to intermittent clouds and poor seeing. Later in the night, with a successful lock on Dione, we obtained 102 images of the transit of Prometheus. We observed for twenty minutes before and after the time of superior conjunction predicted using the orbital lag measured by French et al. (1998). Of these images, 18 ultimately provided useful measurements of the position of Prometheus.

On 13 November, the closest bright satellite to Saturn's south pole was Tethys, which was located northwest of Saturn, $29''$ away from the target area but only $10''$ from the rings (see Fig. 2.) The opportunity to image Prometheus was lost when the PALAO system could not be locked onto Tethys. We attributed this to the strong gradient of scattered light from the rings in the WFS images. Rhea, which was north of Saturn and $52''$ from the south pole, proved to be a better guide object although the large separation degraded the image quality. Unfortunately, our second and last attempt to image Pandora was thwarted when the computer controlling the AO system crashed just before Pandora was predicted to enter the gap. By the time the computer had been rebooted, the opportunity was lost. Pandora was not detected in any of the images taken before or after the computer crash.

Janus and Epimetheus were present in the 50 images taken during our attempt to image the transit of Pandora. Due to the relative brightness of these satellites and the excellent quality of the images, they could be easily detected even far away from the south pole where the planet covered the rings.

3. Astrometry

The images were flat-fielded in the normal manner using twilight flats.

Four images from 13 November contained three bright satellites, Dione, Tethys and Rhea, all in the same frame (see Fig. 2). Their positions were measured using a simple centroiding algorithm and compared to an ephemeris from the Planetary Data System Rings Node (http://ringside.arc.nasa.gov) which uses JPL ephemerides SAT077 and SAT081. This allowed us to compute a plate scale for the camera of $0.0401''$ per pixel, very close to the nominal value of $0.04''$ per pixel. The orientation of the array was also determined, and the y-axis of the image was found to be tilted $1.06°$ east of J2000 north.

To determine the location of the center of Saturn in each image, the position of a bright satellite (Dione on 9 November and Tethys on 13 November) was measured using the centroiding algorithm and the satellite ephemeris was used to compute its offset from Saturn's center of mass. Each image was then shifted to place the center of Saturn at the center of the image. To remove the scattered light from the rings, eight suitable images were median-filtered to produce a template of the rings, which was then subtracted from the individual images.

Janus was easily measured in the 13 November images as the moon traveled under the south pole of Saturn, including images taken before and after Janus traversed the gap. To facilitate accurate astrometry, three or four images were coadded, with the later images shifted by the expected motion of the moon to prevent smearing. Janus' position was found to be in excellent agreement with the ephemeris (SAT081). Our measurements are given in Table 2.

Epimetheus was measured in a similar way, in the same images, but the measured positions did not agree well with the ephemeris values (from SAT081). Epimetheus, which is somewhat fainter than Janus, was imaged near eastern elongation, where the gradient of scattered light from the rings was stronger than that near the south pole. Despite the template subtraction, the removal of scattered light from the rings was not 100% effective, and Epimetheus' apparent position was displaced radially inward by ~ 4 pixel (or $\sim 10^3$ km) with respect to its ephemeris position. As this error is roughly perpendicular to the direction of orbital motion, it is highly unlikely to represent a real ephemeris error and we do not report the measured positions here.

The most interesting observation was Prometheus' transit of the south pole on 9 November. Because it is so faint, Prometheus' position could not be measured using centroiding algorithms, but was estimated by eye to within ± 3 pixels. This method was as effective in single images as it was in coadded images, so Prometheus was measured in individual 10-sec exposures to avoid any bias that might be introduced by shifting and coadding. The measured offset in right ascension of Prometheus relative to the center of Saturn was plotted vs. time in Fig. /reff:promplot. At the limb, the south pole of Saturn is $0.35''$ east of the center of the planet. The predicted time of superior conjunction from the Rings Node ephemeris (SAT101) based on the Voyager-era orbital fit of Synnott *et al.* (1983) was 10:58:50 UT. According to our observations, Prometheus passed the south pole at $11:52:42 \pm 15$ s UT, or 53.8 ± 0.3 min later. The mean motion of Prometheus is $587°$ day^{-1}, so this corresponds to a lag of $21.9 \pm 0.3°$ in mean longitude.

Fig. 4 shows a sequence of coadded, template-subtracted images acquired as Prometheus passed below Saturn's south pole.

4. Discussion

A joint analysis of Hubble Space Telescope (HST) data sets from May, August and November 1995 found an average orbital lag for Prometheus of 18.85±11°, which did not vary significantly over the 183 day span of the observations. The uncertainty in the orbit fit to the Voyager data by Synnott *et al.* (1983) could only account for an error of ∼2–3°. However, as noted above, a continuing campaign of observations by French *et al.* (2000) shows the lag to be increasing at a rate of $0.57°\mathrm{yr}^{-1}$, implying a lag of 21.7° in November 2000. This is in good agreement with our observations.

The orbital eccentricity of Prometheus was measured to be 0.0015±0.0009 during the ring-plane crossing (McGhee *et al.* 2001) and 0.00169±0.000039 (French *et al.* 2000) from continuing observations. Both values are somewhat smaller than the Voyager-era eccentricity of 0.0024±0.0006 (Synnott *et al.* 1983), though the error bars overlap. The combination of our adaptive optics observations at superior conjunction with near-simultaneous observations by French et al. near elongation may permit a refined estimate of Prometheus's orbital eccentricity.

Although Pandora and Prometheus remain challenging targets for Earth-based observers, the position of Janus was measured with little difficulty, and both it an Epimetheus could be routinely observed with many AO systems. The next opportunity to observe Pandora and Prometheus in a similar geometry will be in February of 2005, coinciding with the Cassini spacecraft's arrival at Saturn.

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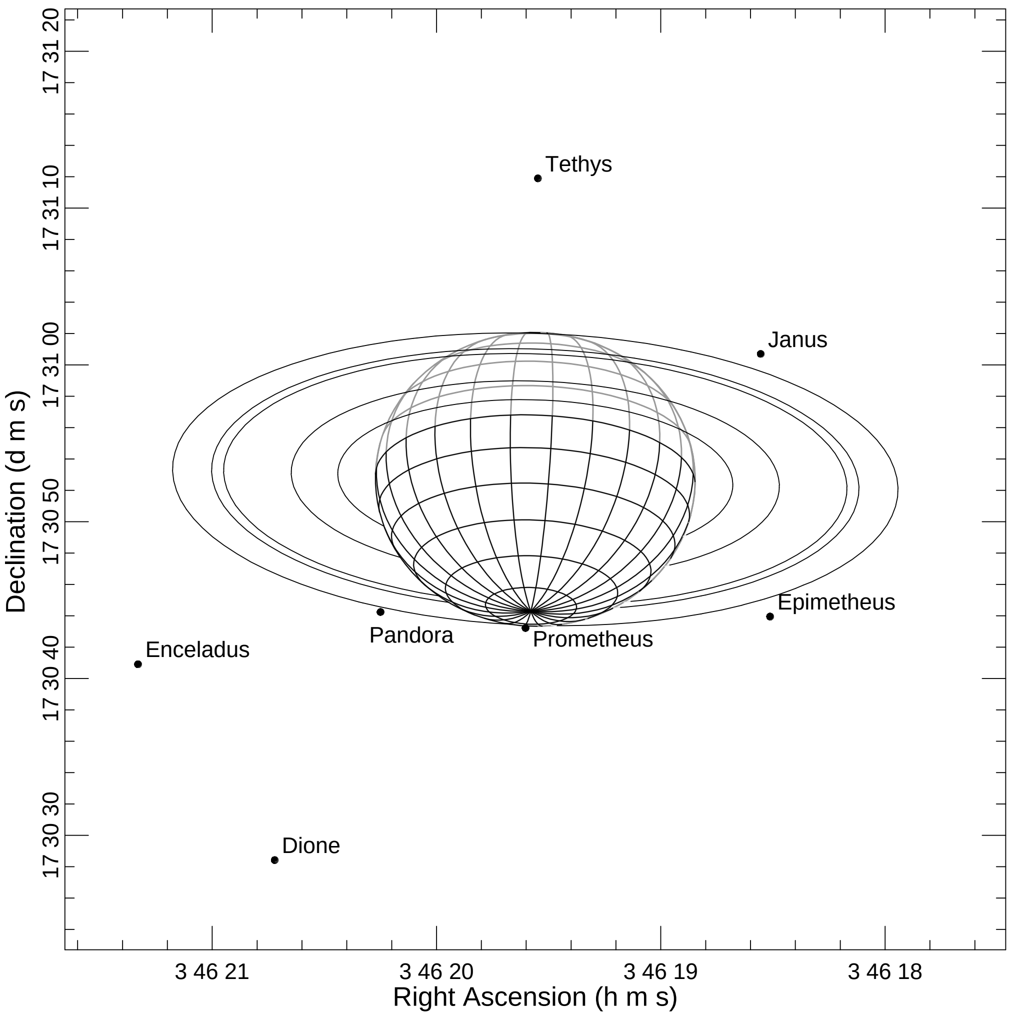

Fig. 1.— Saturn, its rings and satellites as viewed on 9 November 2000 at 11:55 UT. The field shown is slightly larger than that of PHARO. The southern limb of the planet occults the rings, but does not cover Pandora and Prometheus as they pass below the south pole. In this diagram, Prometheus has been shifted forward 19° of longitude relative to the Voyager-era orbit. Dione was used as the guide object for the AO system on this night as well as an astrometric reference.

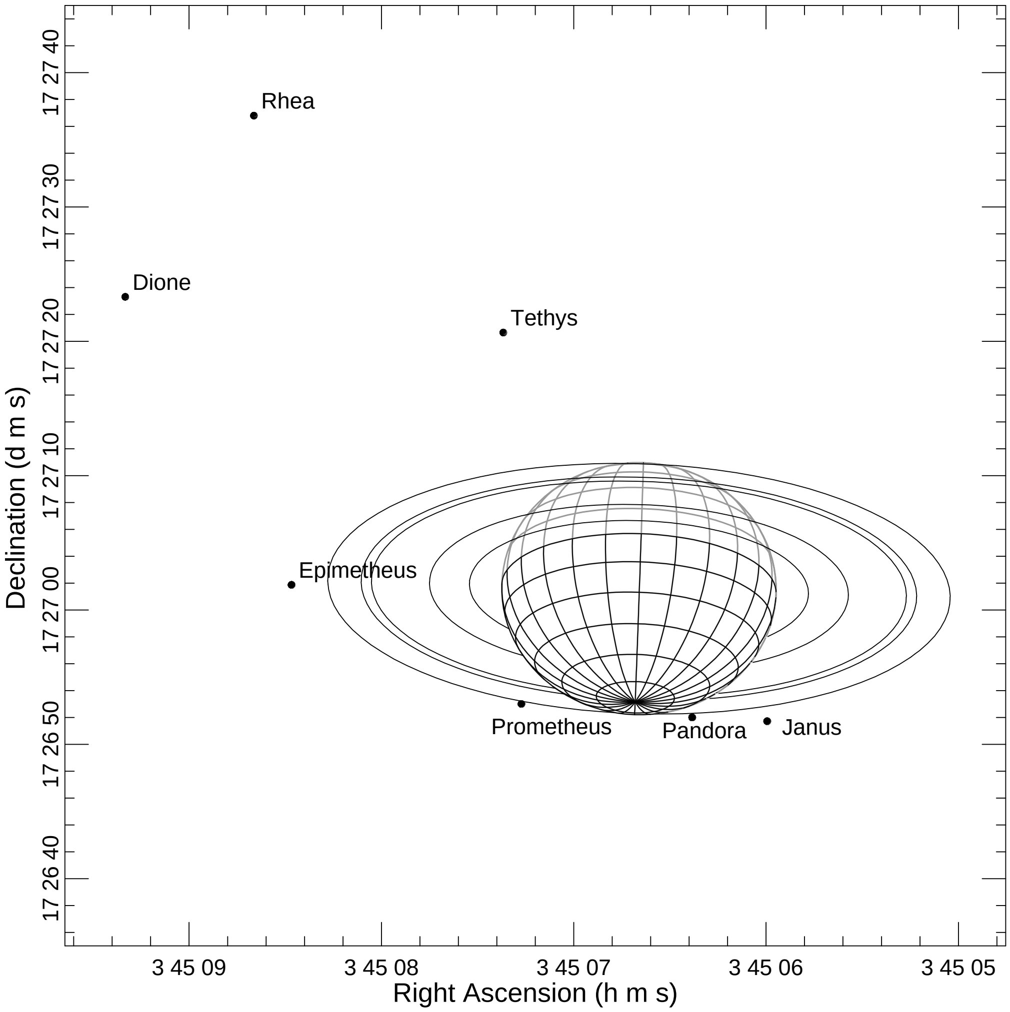

Fig. 2.— Saturn, its rings and satellites as viewed on 13 November 2000 at 5:00 UT. Prometheus has again been shifted forward 19° of longitude relative to the Voyager-era orbit. Epimetheus was near eastern elongation, while Janus also transited the south pole. Dione, Rhea and Tethys were available as guide objects and astrometric references.

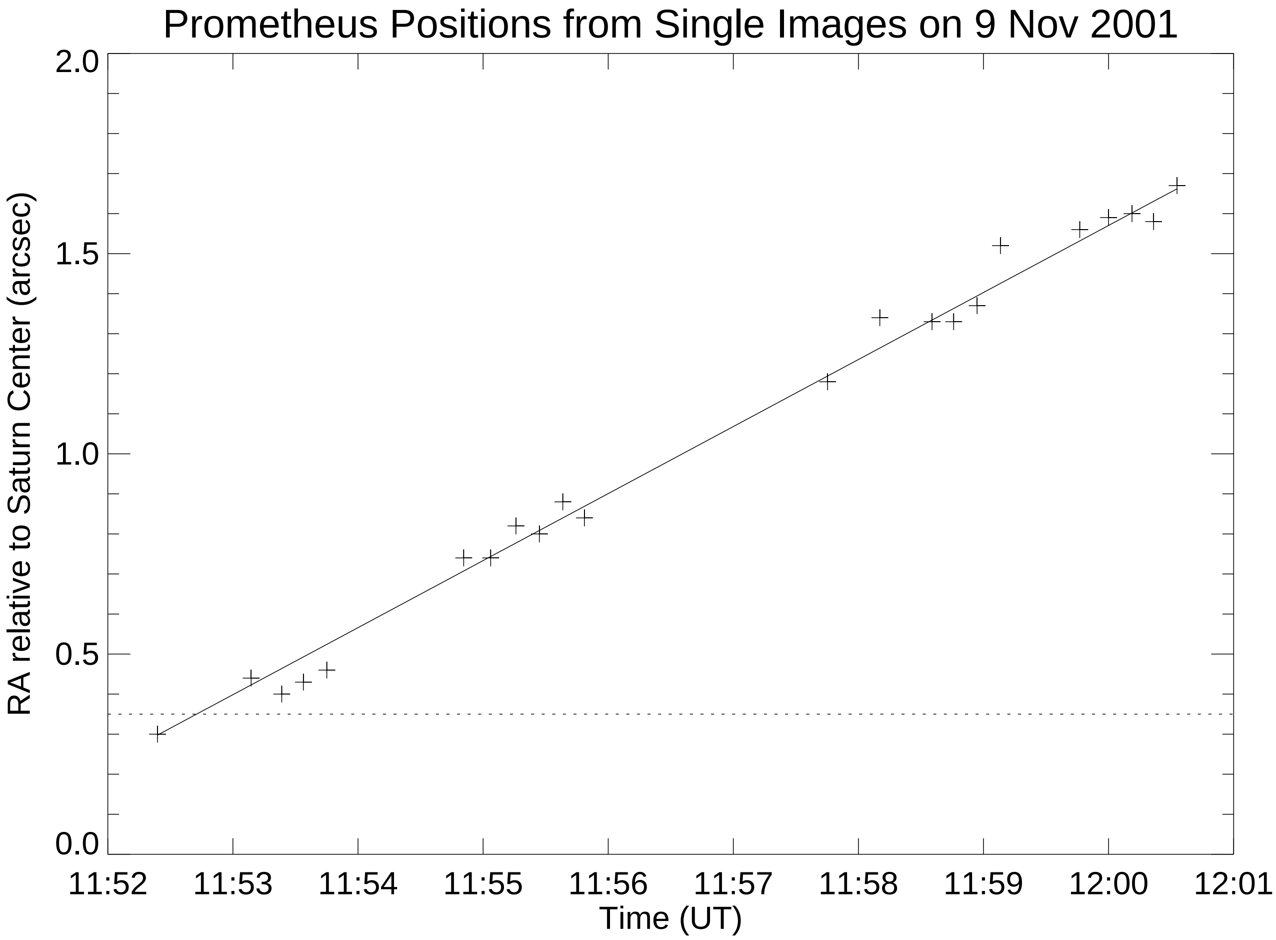

Fig. 3.— Prometheus' measured offset in right ascension relative to the center of mass of Saturn, plotted as a function of time. The solid line is a linear fit to the data. The dotted line indicates the right ascension of the south pole of Saturn.

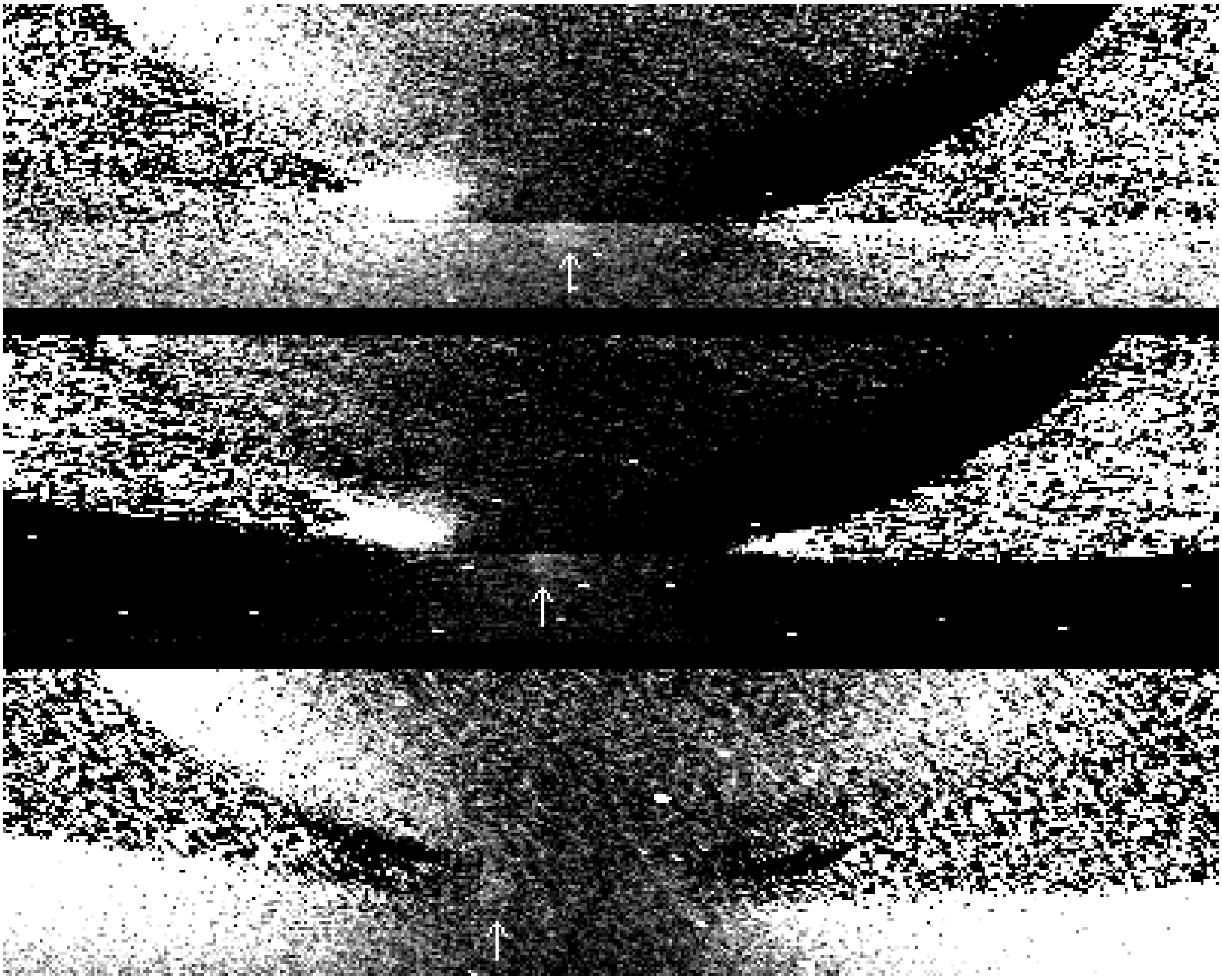

Fig. 4.— Prometheus, as it moves below the south pole of Saturn. At 2.2 μm, the planet's southern limb is dark and the rings are saturated. The scattered light from the rings has been largely removed by subtracting a ring template. Each frame in this figure is the sum of three template-subtracted images. The top image is the sum of images 87–89, the middle, 93–95, and bottom, 102–104. (See Table 1.)

Table 1. Measured Planetocentric Coordinates of Prometheus on 9 November 2000 (UT).

		Offsets (″)	
File	UT Time	$\Delta\alpha$	$\Delta\delta$
86	11:52:23	0.30	-9.57
87	11:53:08	0.44	-9.52
88	11:53:23	0.40	-9.53
89	11:53:33	0.43	-9.55
90	11:53:45	0.46	-9.56
93	11:54:50	0.74	-9.42
94	11:55:03	0.74	-9.45
95	11:55:15	0.82	-9.49
96	11:55:26	0.80	-9.50
97	11:55:38	0.88	-9.48
98	11:55:48	0.84	-9.42
99	11:57:45	1.18	-9.41
100	11:58:10	1.34	-9.42
102	11:58:35	1.33	-9.36
103	11:58:45	1.33	-9.30
104	11:58:56	1.37	-9.36
105	11:59:08	1.52	-9.37
106	11:59:46	1.56	-9.42
107	12:00:00	1.59	-9.33

Table 1—Continued

		Offsets ($''$)	
File	UT Time	$\Delta\alpha$	$\Delta\delta$
108	12:00:11	1.60	-9.35
109	12:00:21	1.58	-9.37
110	12:00:32	1.67	-9.38

Table 2. Measured Planetocentric Coordinates of Janus on 13 November 2000 (UT).

File numbers	UT Time	Offsets ($''$) $\Delta\alpha$	$\Delta\delta$
98–101	5:10:43	-7.95	-10.08
102–104	5:11:57	-7.76	-10.09
105–107	5:12:58	-7.61	-10.11
108–110	5:13:31	-7.52	-10.12
111–113	5:14:32	-7.37	-10.13
114–117	5:15:28	-7.22	-10.14
118–121	5:16:47	-7.02	-10.16
122–124	5:17:42	-6.88	-10.17
132–135	5:44:09	-2.71	-10.37
136–138	5:45:03	-2.57	-10.37
139–141	5:45:42	-2.47	-10.37
142–145	5:46:26	-2.35	-10.37
146–149	5:47:20	-2.21	-10.37
150–153	5:48:10	-2.08	-10.37
154–157	5:49:07	-1.92	-10.37
158–160	5:49:58	-1.79	-10.37
164–167	5:51:49	-1.49	-10.37
168–170	5:53:47	-1.18	-10.37
171–173	5:54:42	-1.03	-10.36

Table 2—Continued

File numbers	UT Time	Offsets ($''$) $\Delta\alpha$	$\Delta\delta$
174–177	5:55:57	-0.83	-10.36
186–189	5:59:29	-0.26	-10.35
190–192	6:00:27	-0.11	-10.34
193–195	6:01:26	0.05	-10.34
196–198	6:02:29	0.22	-10.33
199–201	6:03:13	0.34	-10.33
202–204	6:04:01	0.47	-10.33
205–207	6:04:42	0.57	-10.32
208–210	6:05:32	0.71	-10.32
211–213	6:06:07	0.80	-10.31
214–216	6:06:56	0.93	-10.31
214–215	6:06:51	0.92	-10.31