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THE STRUCTURE OF PLUTO'S ATMOSPHERE FROM THE 2002 AUGUST 21 STELLAR OCCULTATION

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ABSTRACT

We have observed the 2002 August 21 occultation by Pluto of the $R = 15.7$ mag star P131.1, using 0.5 s cadence observations in integrated white light with the Williams College frame-transfer, rapid-readout CCD at the 2.24 m University of Hawaii telescope. We detected an occultation that lasted 5 minutes, 9.1 ± 0.7 s between half-light points. The "kinks" in the ingress and egress parts of the curve that were apparent in 1988 had become much less pronounced by the time of the two 2002 occultations that were observed, indicating a major change in the structure of Pluto's atmosphere. Analysis of our light curves shows that the pressure in Pluto's atmosphere has increased at all the altitudes that we probed. Essentially, the entire pressure scale has moved up in altitude, increasing by a factor of 2 since 1988. Spikes in our light curve reveal vertical structure in Pluto's atmosphere at unprecedentedly high resolution. We have confirmation of our spikes at lower time resolution as part of observations of the emersion made at 1.4 s and 2.4 s cadence with the 3.67 m AEOS telescope on Maui.

Key words: occultations — planets and satellites: individual (Pluto)

1. INTRODUCTION

Of the variety of techniques that can be used to provide the highest spatial resolution on astronomical objects, those of occultations and transits are especially powerful. Using the motion of one object to be covered by or to cover fine structure on or around another can provide high resolution limited only by Fresnel diffraction. Occultations also directly probe the atmosphere itself, as the light measured travels through the atmosphere and therefore is very sensitive to atmospheric conditions.

Transit techniques can be used to provide high spatial resolution on the Sun. They are being increasingly used to discover or confirm planets around other stars and have the potential even to disclose structure on the surfaces of those stars (Deeg et al. 2001). Back in our own solar system, they have been used to study Mercury at the 1999 and 2003 transits (Schneider et al. 2001, 2004) and to study Venus at the 2004 June 8 transit, the first such since the year 1882 (Pasachoff et al. 2004, 2005). But stellar occultations can provide higher resolution (Elliot & Olkin 1996), due to the small angular diameter of the star.

Before 2002, Pluto's atmosphere had previously been probed only with the occultation of 1988 from the Kuiper Airborne Observatory (KAO; Elliot et al. 1989) and the ground (Hubbard et al. 1988; Millis et al. 1993). The data from a grazing occultation in 1985 (Brosch 1995) were recorded under challenging conditions, and the drop attributed to an occultation by Pluto may be due to something else. Our Williams College–MIT–Lowell team attempted to observe the 2002 July 12 Pluto occultation of the star P126, with limited success—though enough to show that Pluto's atmosphere had changed since 1988 (Buie et al. 2002). The path for this occultation crossed north of the major telescopes in Chile that we were using (although wind and bad weather prevented their use in any case), and south of the major telescopes on the Canary Islands with which we had established collaborations. Only one of our portable telescopes succeeded. Another group also observed this event, and they also conclude that Pluto's atmosphere had changed (Sicardy et al. 2003).

The 2002 August event was observed by our group with nine telescopes at five sites in Hawaii and on the US mainland, with data recorded at visible and near-infrared wavelengths (Elliot et al. 2003b). Our first analyses of these data confirmed our conclusion from the July event that Pluto's atmosphere had considerably changed between 1988 and 2002. Furthermore, we found that (1) Pluto's atmospheric pressure, measured at the half-light level (1250 km radius) had increased by a factor of 2, (2) the equivalent isothermal temperature in the upper part of the region probed by the occultation had not changed perceptibly since 1988, (3) prevalent light-curve "spikes" indicate significantly more dynamical activity (waves or turbulence) than in 1988, and (4) the structure of occultation light curves varies with wavelength in a manner consistent with extinction

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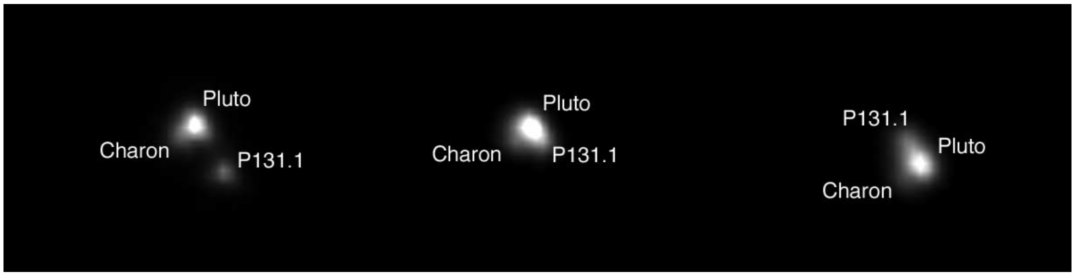

FIG. 1.—Extracts of a sequence of images taken with the WCCCD at the UH 2.24 m telescope, showing Pluto, Charon, and the star occulted by Pluto. Note that Pluto and Charon are distinguishable, though not completely separated. Each of the images was taken with no binning and $0\farcs2$ pixels. The first is 20 m before mid-occultation, the second is 10 m before mid-occultation, just before we made a 20 minute run with 5×5 binning, and the third is 10 minutes after mid-occultation.

by small particles in Pluto's atmosphere (Elliot et al. 2003b). The method of inversion has been discussed in the Pluto context by Elliot et al. (2003a).

In this paper, we extend the analysis of the University of Hawaii 2.24 m and Haleakala data, with an emphasis on gaining a deeper understanding of the nonisothermal features and possible asymmetry in the occultation light curves. Since the locations of the two telescopes differ by 121 km perpendicular to the motion of Pluto's shadow, comparison of these light curves allows us to probe the horizontal structure of Pluto's atmosphere. We then compare our conclusions with those of Sicardy et al. (2003), who also observed the two 2002 Pluto occultations. Hubbard (2003), in an unrefereed solicited comment on the Elliot et al. (2003b) and Sicardy et al. (2003) papers, evaluated the effect of the nitrogen vapor pressure and the ramifications for NASA's prospective *New Horizons* mission to Pluto.

2. OBSERVATIONS

We used the Williams College CCD (WCCCD) installed on the University of Hawaii's 2.24 m telescope on Mauna Kea. On 2002 August 21, we observed the occultation of a star called P131.1 (McDonald & Elliot 2000), using positions regularly updated on the World Wide Web as they were being refined by our astrometry efforts.[3] The reference position for P131.1 in J2000 coordinates is R.A. = $16^{\rm h}58^{\rm m}49\fs456$, decl. = $-12^\circ51'31\farcs41$ (McDonald & Elliot 2000).

We observed in broadband with no filter, in order to maximize the throughput. The star has $R = 15.7$ mag. The WCCCD's sensitivity, combined with an approximate spectrum for a star with $R-K = 2.4$, peaks at approximately 0.75 μm (see Fig. 3 of
Q1 Elliot et al. 2003b). (Other members of our team, at other telescopes, observed in the infrared.) At the time of the observation, we had no information on the star's possible duplicity, other than that it appeared single. Since then, M. C. Liu has kindly observed it for us with the Subaru Adaptive Optics System with approx-
Q2 imately $0\farcs2$ FWHM in the K band. No companion was seen; any companion with ΔK of 4.5 mag would have been seen outside of $0\farcs65$ separation, and any with $\Delta K \sim 5.5$ outside of $\sim 2''$ (M. C. Liu 2003, private communication), so we conducted all analyses based on the star's being single.

The WCCCD is a Princeton Instruments (now part of Roper Scientific) TE/CCD-576E frame-transfer system. The imaging area consists of 22 μm $\times$ 22 μm pixels, in a 288×384 array. At 109 μm arcsec^{-1} at the telescope's focus, our CCD resolution was essentially 5 pixels arcsec^{-1}. Its readout speed is adjustable, and at this Pluto occultation we ran it at 2 Hz. Images were exposed for 498 ms and then transferred to the readout frame in 2 ms. There is no camera "dead time," but during the transfer process, pixels in a given column are exposed to incident light from other portions of that column. Since most pixels in any given column see no significant light, the impact of this frame-transfer process on our data amounts to a loss of only 0.4% in integrated intensity. During each 0.5 s exposure, Pluto's shadow advanced along its track by only 3.4 km, which is slightly less than the 3.6 km shadow motion for a single integration for the KAO data recorded for the 1988 occultation (Elliot et al. 1989). Hence these data provide (by a small margin) the highest spatial resolution so far achieved in Pluto's occultation shadow.

The sky was mostly clear and seeing was excellent, with FWHM measurements of the point-spread function ranging from about $0\farcs4$ to $0\farcs5$; Charon was readily visible alongside Pluto throughout the night, though the two objects were not completely separated (Fig. 1). We monitored transparency with a double star in the field. The Pluto-star separation was predicted to diminish to only $0\farcs04 \pm 0\farcs01$. At the time of occultation, Pluto was 30.24 AU from Earth. From a circular astrometric solution involving the Lick and University of Hawaii (UH) 2.24 m light curves, Elliot et al. (2003b) derived that the closest approach of the star to the center of Pluto's shadow was 597 ± 32 km at our site.

The occultation was predicted to begin at UT 06:48:21 and end at 06:52:25, with a central time of 06:50:23, giving a predicted duration (from half-flux at ingress to half-flux at egress) of 4 minutes and 4 seconds (=244 s). We surrounded the occultation with extra time, to a total of 20 minutes, to provide a good baseline and to allow for serendipitous events. At 2 Hz, we thus had approximately 500 data points within the occultation out of 2400 data points total. We detected an occultation that lasted 5 minutes, 9.1 ± 0.7 s between half-light points. We could see the effects of the occultation for 6 minutes, 34 s (=394 s), which, even after accounting for the differences between "first and last effects" and the half-flux levels, was substantially longer than the expected event duration, indicating, as noted above, that the occultation occurred with a minimum separation between our site and the center of Pluto's shadow that was smaller than the pre-event prediction value of 810 km.

During the occultation run, we binned our pixels 5×5 (on the CCD) to reduce readout noise, giving a resolution of $1''$ at the image plane of the UH 2.24 m telescope. Before and after the occultation, we obtained images at our maximum resolution of 1×1 pixel, or an image resolution of $0\farcs2$, for astrometric calibration of the event.

Observations were made with the Advanced Electro-Optical System (AEOS) 3.6 m telescope on Haleakala at the Maui

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[3] See http://occult.mit.edu/research/occultations/Candidates/Predictions/P131.1.html.

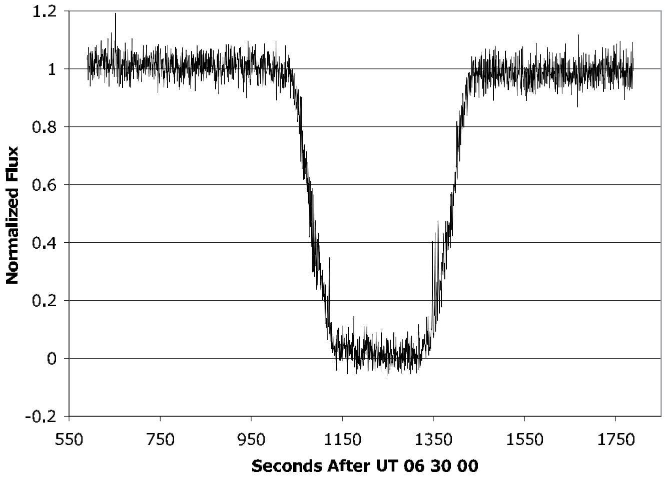

FIG. 2.—Williams College light curve for the Pluto occultation of 2002 August 21. The plot is in calibrated P131.1 flux vs. time.

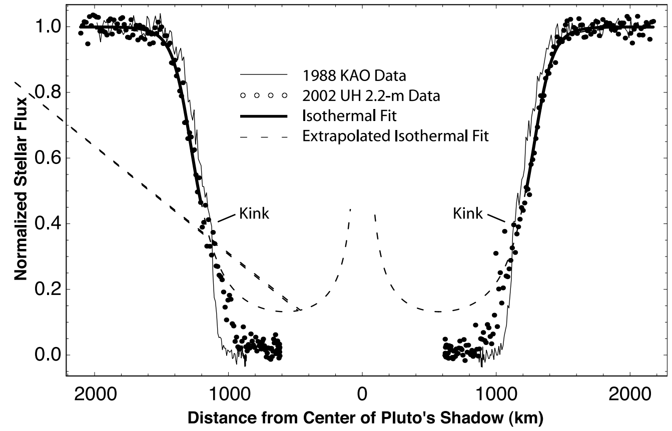

FIG. 3.—Comparison of 1988 and 2002 light curves with an isothermal model. The prior P8 KAO light curve and our P131.1 light curve (made with the Williams College CCD on the UH 2.24 m telescope) are plotted with respect to distance from the center of Pluto's shadow. The thin solid line indicates the 1988 light curve, while the points indicate the new 2002 data. The locations of the "kinks" in the 1988 data are indicated. Neither occultation was central on Pluto's shadow, resulting in the lack of data near the center of the plot. The 2002 P131.1 light curve has been binned to the approximate resolution of the KAO data. Overlaid is an isothermal model (Elliot & Young 1992) fit to the 2002 data, with the central flash truncated. The thick line shows the region where the model was fitted to the data, while the dashed line indicates the isothermal extrapolation from this fit. Note the expansion of Pluto's atmosphere as seen by the increase in overall width of the 2002 light curve as compared with the 1988 data. Note that the sudden change of slope (kink) just below half-light on ingress and egress in the 1988 event is not apparent in the current light curve.

Space Surveillance System. The observations used the Visible Imager camera (VisIm). The camera is the main science camera for the AEOS adaptive optics system, but it can be used for non–adaptive optics observations (Roberts & Neyman 2002). The VisIm is a frame-transfer camera with a 512 × 512 pixel EEV CCD. The dark current is 22 e^- pixel^{-1} s^{-1} at a temperature of −40°C. The read noise is 12 e^- rms. The camera output is digitized to 12 bits with 10 e^- per count. Quantum efficiency varies from 45% at 700 nm to 10% at 1050 nm over the VisIm normal optical bandpass. It is a 12 bit camera, which does not allow for a large dynamic range but does allow for fast readout times. The maximum frame rate is 4.5 Hz. Exposure times can be set as short as 10 ms. The VisIm has three fields of view: 10″, 26″, and 65″.

These Maui observations started at 6:51:50 UT and lasted till 7:04:46 UT. They started late because of technical difficulties, past the center of the occultation, but succeeded in observing the egress. The observations from 6:51:50 to 6:53:38 UT had an exposure of 998 ms. After this, the exposure was set to 1998 ms. There were 402 ms of dead time between successive frames. These observations used the camera's 65″ field of view to maximize signal-to-noise ratio (S/N) and were made in the Bessell *I* band.

3. LIGHT-CURVE EXTRACTION

The Mauna Kea 2.24 m CCD data were analyzed in the standard manner, considering darks and flat fields and using a nearby double star in the field on the chip as a photometric comparison. The light curve we extracted is displayed in Figure 2 using a 4.0 pixel radius (the scale was approximately 1″.0 pixel^{-1}) for exact circular-aperture photometry. The extraction was repeated for aperture sizes from 1.0 to 7.0 pixels to confirm the robustness of this result, and the 4.0 value was found to have the highest signal-to-noise ratio. The final light curve yields a S/N of 103 per atmospheric scale height of shadow motion (∼60 km). Since distance of the occultation from the center of the occultation shadow is an important parameter, we have also plotted the
Q3 curve with that as the independent variable in Figure 3. In that curve, we have also overplotted the data from the 1988 KAO observations (Elliot et al. 1989), as well as an isothermal model (Elliot & Young 1992).

The Maui data were similarly debiased, dark-subtracted, and flat-fielded. The light curve was extracted with the IDL implementation of DAOPHOT's aperture photometry routine. The resulting light curve is given in Figure 4.

4. ANALYSIS OF OVERALL LIGHT CURVE

In Figure 3, it is clear that the overall height of the atmosphere, as shown by the width of the upper half of the light curve, detected in 1988 is less than that of 2002, marking a significant change in Pluto's atmosphere over the 14 year interval. Elliot
et al. (2003b; see their Fig. 3) have shown from infrared spectral Q4
observations of the occultation that at some point in the light curve, extinction effects become significant. The extinction effect on the 2002 light curve is significantly different than it was in 1988 and must be modeled differently—a task beyond the scope of this paper. Here we have chosen to analyze the light

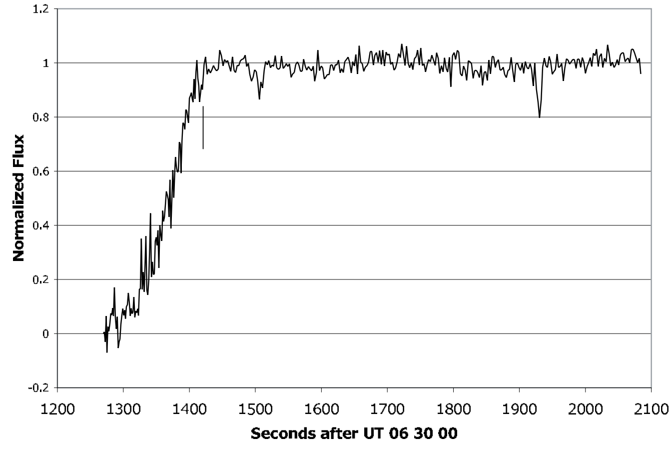

FIG. 4.—Light curve measured with the AEOS telescope on Maui, which covered only the egress. The cadence is 1.4 s during the emersion and 2.4 s afterward. A vertical line indicates the time of the cadence change.

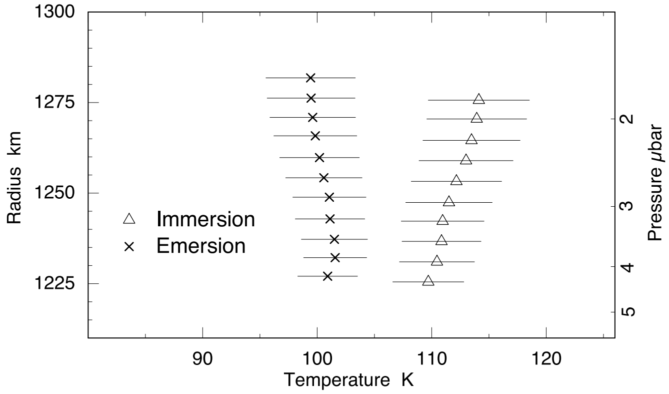

FIG. 5.—Temperature inversion results. The 2002 P131.1 data were inverted using the methods of Elliot et al. (2002). The resulting temperature profiles for both the occultation ingress and egress are plotted. Pluto's surface radius is 1175 ± 25 km. A pressure scale is given on the right-hand axis. Note that these temperature profiles are consistent with the derived isothermal equivalent temperatures of 107 ± 4 K for ingress and 101 ± 3 K for egress. The inversions were carried out down to 1220 km to be consistent with the region of the atmosphere used in the isothermal model fitting. The lack of complete agreement between these two temperatures may result from a global temperature gradient.

curve corresponding to the region in Pluto's atmosphere above 1220 km from the planet's center, under the assumption that this portion of the atmosphere is clear. Below this level, the atmosphere markedly deviates from the isothermal model that fits the upper part of the light curve (Fig. 3).

Using the model described by Elliot & Young (1992), we derived isothermal atmospheric temperatures for a clear, molecular nitrogen atmosphere: 107 ± 4 K for ingress and 101 ± 3 K for egress (Elliot et al. 2003b) for the region of our light curve shown by the solid line in Figure 3, which corresponds to radii above 1220 km within Pluto's atmosphere. These values, and their mean of 104 ± 2 K, are essentially the same as the 104 ± 8 K derived for 1988, meaning that there is no evidence for a temperature change at these high atmospheric levels. The derived temperature profiles for both ingress and egress are displayed in Figure 5. The boundary condition for these inversions was set by an isothermal fit to the portion of the light curve above the inversion region (Elliot et al. 2003a). Pressure inversions of our light curve (Elliot et al. 2003b) show an increase by a factor of approximately 2 in the pressure between 1988 and 2002 for the radius range 1220–1280 km. The surface pressure has probably increased by the same factor.

Such a change in pressure could be caused by a 1.3 K temperature increase of the nitrogen ice on Pluto's surface (Elliot et al. 2003b). These observations match a prediction of a pressure increase with a peak reached in ~2005, persisting until ~2025 (Hansen & Paige 1996, Fig. 11). Alternatively, or in part, Pluto's high inclination and thermal inertia can continue to raise its temperature despite the epoch 13 years after its 1989 perihelion. Since in this model the trend should stop and reverse, it is important to continue monitoring Pluto's atmospheric pressure at future occultations, and we have received a grant from NASA for improved equipment to do so.

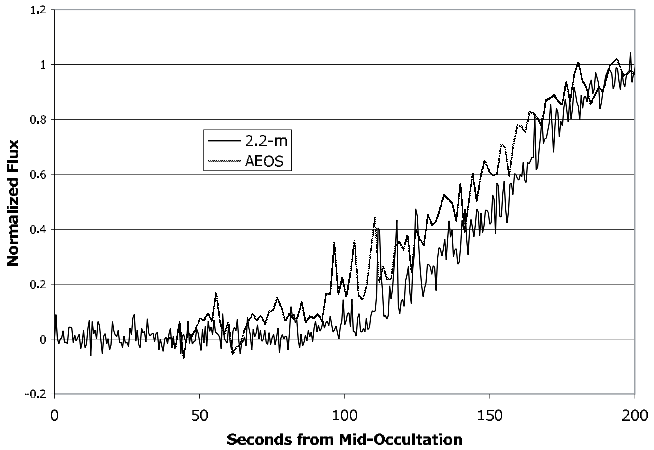

FIG. 6.—Close-up of the Williams College data for the egress spikes, at a cadence of 0.5 s, and an overplotted close-up of the AEOS data for the egress spikes, at a cadence of 1.4 s.

The common increase in temperature of Pluto and of Triton (Elliot et al. 1998) prompted us to examine the total solar irradiance (TSI), formerly known as the solar constant, over the period in question (Fröhlich & Lean 1998; Fröhlich 2002). A variation with the period of the solar activity cycle provides variations of 0.5% but no long-term trend greater than 0.05% per decade of troughs at solar minima (Willson et al. 2003), and even that variation of the trough depth is not widely accepted.[4]

The light-curve of Sicardy et al. (2003) for the 2002 August 20 event showed a slight decline of the intensity with time during the central part of the occultation, something that did not appear in our data. They were observing using the Canada-France-Hawaii Telescope (CFHT), which is adjacent on Mauna Kea to the 2.24 m telescope we were using, so the difference is likely not a real effect in Pluto's atmosphere.

5. ANALYSIS OF SPIKES

The inclined portions of the light curves, at both ingress and egress, reveal sharp increases in brightness, long known as "spikes." The spikes at egress from both the 2.24 m UH telescope on Mauna Kea and the AEOS telescope on Maui, 121 km separated from each other, are shown in Figure 6. A basic discussion of using spikes seen at stellar occultations, notably the 1971 May 13 occultation of β Scorpii by Jupiter and the 1968 April 7 occultation of BD $-17^\circ 4388$ by Neptune, to probe atmospheric structure and composition was provided by Elliot & Veverka (1976). More recent studies of occultation phenomena, including spikes, have been summarized by Elliot & Olkin (1996). They point out that the one or two spikes seen in the 1988 Pluto data mean that Pluto's atmosphere has fewer waves or turbulence than the giant planets' atmospheres, which show more spikes.

The high time resolution we obtained with the WCCCD was necessary for satisfactory analysis of the spikes, since approximately four data points were detected within each at our 0.5 s cadence. Thus the 1.4 s cadence for egress at Maui (this paper) was sufficient to capture the existence of spikes but not to map their intensity reliably, since with only about one data point per spike it is not possible to tell where within the spike the exposure came or how the spike intensity is averaged over the exposure duration. The CFHT data, which were obtained from a telescope adjacent to our Mauna Kea telescope, published by Sicardy et al. (2003) show spikes, but are at 1.5 s cadence with a 0.6 s gap between frames, also limiting the accuracy of the determination of the timing and intensity of the spikes. The time

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[4] The TSI, measured from space, from 1978 to the present is available on the World Wide Web at http://www.acrim.com and http://www.pmodwrc.ch/pmod.php?topic=solar_const.

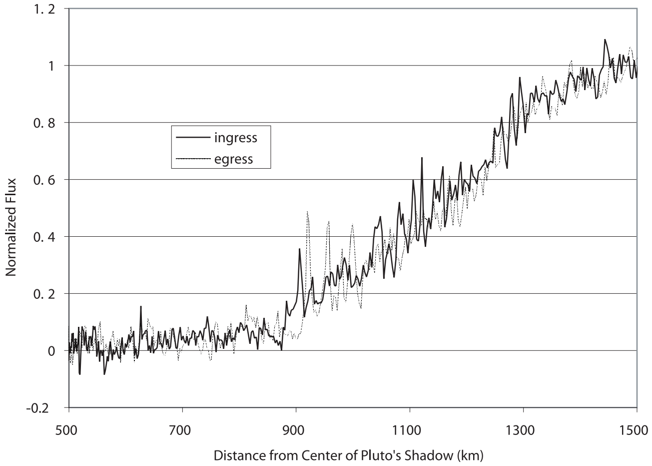

Fig. 7.—Close-up of the Williams College data for the ingress and egress spikes, with the background trend removed and with the ingress direction flipped to make alignments apparent. The graph shows normalized stellar flux plotted vs. distance from the center of Pluto's shadow. (The distance scale in the shadow is different from the radius scale at the planet because of refraction. For the explicit transformation, see eq. [5] of Elliot et al. 2003a.)

resolution of the KAO data was 0.2 s, which, coupled with the shadow velocity of 18.48 km s^{-1} (Elliot & Young 1992), yields a spatial resolution of 3.70 km in Pluto's shadow. The spatial resolution in Pluto's shadow for the UH 2.24 m data set is somewhat better: 3.43 km, as derived from the 0.5 s time resolution and the shadow velocity of 6.85 km s^{-1}.

The spikes, following the analysis of Elliot & Veverka (1976), reveal vertical structure in the density of Pluto's atmosphere, leading to changes in the refraction. The spikes were well resolved in time, so the differences between the spikes at ingress and egress reveal horizontal structure. Horizontal structure would also be demonstrated by any differences that we could establish between our sites on Mauna Kea and Maui, 121 km apart, though our ability to do so is vitiated by the lower time resolution of the Maui telescope.

Initially, we examined whether or not the spikes appearing during ingress occur at the same altitude as the spikes present in egress. If so, this might indicate a symmetric atmospheric disturbance. A set of spikes at 112, 118, and 125 s from mid-occultation on egress is not quite matched by a single spike at 115 s on ingress. These spikes quintuple the brightness of the adjacent starlight. A lesser set of three spikes are also visible at 165, 168, and 171 s on immersion.

The 2.24 m data were then replotted as radial distance (from Pluto) versus normalized intensity as in Figure 3, but folded such that the ingress and egress curves lie atop one another (Fig. 7). There are eight distinct spikes in this blown-up region of the plot. None of these spikes coincide; however, they all occur in the lower half of the atmosphere. The most likely conclusion from this analysis is that we observed an asymmetric atmospheric disturbance; however, a logical possibility is that the disturbance moved to a lower point in the atmosphere during the 4 minutes of full occultation.

Next we compared the UH 2.24 m data with data from the Air Force telescope on Maui. The goal was to see if the spikes that appear in the UH 2.2 m data are also present in the Maui data. The data were transformed from a time versus intensity array to a distance versus intensity array using a cubic spline interpolation of points to account for the nonuniform intervals between exposures in the Maui data. Again, the spikes do not coincide, indicating that the spike-causing disturbances are at different altitudes on opposite sides of the planet. A shift of 20 km of the 120 km horizontal distance (in the shadow) probed by the two stations significantly improves the spike alignment as seen in Figure 8. Since the light-curve flux at that level is ~0.2, this shift would be ~4 km within Pluto's atmosphere. Such a small vertical displacement over a short distance may indicate that the two stations were observing the same small-scale disturbance that varied slightly in altitude. Alternatively, the shift might be an artifact of a timing uncertainty we have been unable to quantify in the Maui data acquisition system.

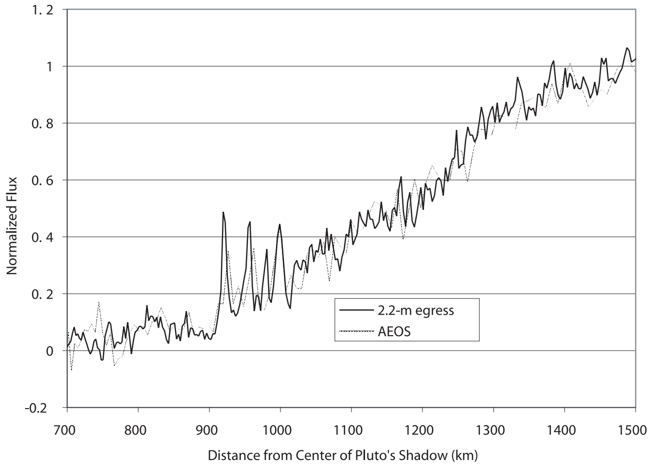

Fig. 8.—Close-up of Williams College–Maui offset spike alignment. The alignment has been improved by shifting the Maui data 20 km higher in the shadow. This shift corresponds to about 4 km within Pluto's atmosphere.

Elliot et al. (1974) used the spikes in Jupiter's atmosphere to find the [He]/[H] ratio, and in principle, we could use this technique to probe minor constituents in Pluto's predominantly N_2 atmosphere (see, e.g., Fig. 14 of Elliot et al. 1977), but that would require detection of the spikes in light curves in multiple, well-defined wavelengths, which is beyond the scope of our data set. French & Lovelace (1983) continued the analysis of spikes, using numerical simulations. Among their results is a discussion of the effects of diffraction in the ray-crossing regime. Although diffraction effects have been identified in occultation light curves for Saturn's atmosphere (Cooray & Elliot 2003), our data do not have sufficient resolution to detect the diffraction patterns that mark the difference between their geometric optics and wave optics calculations. French & Lovelace (1983) conclude that their simulations are consistent with the ability of numerical inversion techniques, such as those shown in Figure 5, to detect large-scale layered atmospheric features.

The most relevant atmosphere with which to compare Pluto's is that of Triton, which shows no spikes, even at much higher S/N (Elliot et al. 1998). So Pluto's atmosphere would seem to be less stable than that of Triton.

6. CONCLUSIONS

Our high time resolution observations of the 2002 August 21 occultation of a star by Pluto have revealed significant vertical and horizontal structure in Pluto's atmosphere. The results of the two 2002 Pluto occultations have shown substantial changes in the atmosphere since the only previous major set of observations, in 1988, were obtained.

The relative motion of the star and Pluto was particularly slow at this occultation. Since our 0.5 s time resolution was able to resolve only a handful of points in each atmospheric spike, it would not have been satisfactory for most other occultations. We thus should obtain equipment capable of observing at a higher data rate. Though our apparatus is itself capable of another factor of at least 5 in cadence, signal-to-noise limitations makes it desirable to have a system with a higher throughput, presumably based on a CCD of higher quantum efficiency. Of course, the signal-to-noise ratio obtained at future occultations depends primarily on the brightness of the occulted star and the size of the telescopes available. In the case of the data presented here, the CCD we usually use on a portable 0.36 m telescope at stellar occultations by planets and satellites and at total solar eclipses was actually used on a fixed telescope of 2.24 m, providing a 50 times improvement in collecting area and thus a 4 mag advantage.

Inversion of our light curves shows that the density and pressure of Pluto's atmosphere above the 1220 km radius has increased by a factor of approximately 2, presumably resulting from an increase in the temperature of the surface nitrogen ice by 1.3 K (Elliot et al. 2003ba), while the atmospheric temperature at these levels has remained constant. Whether these increases come from a darkening of Pluto's surface, from thermal inertia, or from some combination of the two should be studied and monitored with future occultation observations. Hubbard (2003) graphs the relation of the heliocentric distance, the average surface temperature, and the nitrogen vapor pressure, showing how abruptly the last of those is expected to fall.

The infrared observations obtained, at lower time resolution than ours, by others at the Infrared Telescope Facility show a trend of the minimum occultation flux with wavelength (Elliot et al. 2003b), which is highly suggestive of extinction in Pluto's atmosphere.

Our data presumably show the effect of a time lag in Pluto's temperature with increasing solar distance, possibly due to large thermal inertia in the surface as proposed for Triton by Spencer (Spencer & Moore 1992; see also Spencer et al. 1997). Pluto has been observed to be darkening since at least 1954, when systematic photoelectric monitoring began (Buie 2002). It is possible that space dust and debris have been accumulating on or modifying its surface, or Pluto's continually changing aspect may indicate significant surface asymmetries.

NASA's *New Horizons* mission, if launched in 2006, would reach Pluto in approximately 2015. There have been suppositions that, given Pluto's increasing distance from the Sun since its 1989 perihelion, its atmosphere will freeze out by approximately that time. Elliot & Olkin (1996) point out how work by Trafton and Stansberry shows that this conclusion depends on the methane or nitrogen states. Our data, and the further data we hope to obtain at future Pluto occultations, should determine long in advance of the spacecraft's arrival whether the atmosphere will be present for close-up observation. The current increase in temperature and pressure seems to prolong the period in which the atmosphere will remain detectable before its collapse, making it more likely that *New Horizons* will be in time for atmospheric studies at Pluto. The current data are consistent with the model of Hansen & Paige (1996, Fig. 11) that shows a cooling beginning ~2015, not far from the spacecraft's prospective arrival. Whether Pluto's atmosphere will ever freeze out depends on the ice equilibrium and is still an open question (Stansberry & Yelle 1999), and a definitive answer is "elusive" (Stansberry 2004). We plan continued occultation observations of Pluto to monitor changes in its atmosphere, using improved cameras.

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Q1 Au: Change from "Elliot et al. 2003" to 2003b correct?
Q2 Au: Added arcseconds to "0.2 FWHM" correct?
Q3 Au: Diagonal lines in Figure 3 spurious?
Q4 Au: Citation changed from 2002 to 2003 correct?
Q5 Au: Pasachoff et al. (2002) is not cited in the text; please either cite or delete.