Stellar Occultations

Chasing the Elusive Atmospheres of Pluto, Eris and other TNOs

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Talk Overview

- Introduction: Pluto, Eris and the Large TNOs
- A Year on Pluto, a Year on Eris
- Stellar Occultations
- Thin Atmosphere Occultations
- Central Flashes
- Titan Occultations

Consider Atmospheres of Icy Bodies

- Mars, Pluto, Triton, Eris & other large TNOs
- As a group (for the purposes of this talk)... they have atmospheres supported by the VAPOR PRESSURE of their surface frosts.
- Earth is not in the group. Our N_2 atmosphere is not supported by vapor pressure.
- Also not in the group: Satellites of Jupiter, Saturn, Uranus and Neptune (except Triton). Their EXOBASES are at their surfaces. Their thin, local atmospheres can still distribute frost on their surfaces, however (e.g., water ice on Enceladus).

Rough Distances & Albedos of some Icy Bodies

Object	Diameter (km)	Perihelion (AU)	Aphelion (AU)	Albedo
Pluto	2350	30	50	0.6
Triton	2707	30	30	0.6
Eris	2320	38	98	0.9
Sedna	1700	76	937	0.1
Makemake	1460	39	53	0.8
2007 OR10	1280	34	101	0.15
Haumea	1300	35	52	0.7

NOTES:

1. Eris' diameter is better known than Pluto's (from occultations). Why?
2. Albedos and diameters for 2007 OR10 ("Snow White") and other TNOs (except for Eris) are based on Spitzer and Herschel/PACS observations.

QUESTION: What are the expected surface temperatures at perihelion? At aphelion?

Expected Surface Temperatures

Object	Diameter (km)	Perihelion (AU)	Aphelion (AU)	Albedo
Pluto	2350	30	50	0.6
Triton	2707	30	30	0.65
Eris	2320	38	98	0.9
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Makemake	1460	39	53	0.8
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Average surface temperature...
Balance heat in (sunlight) with heat out (thermal radiation)

$L_{SUN} \cdot (1\text{-Albedo}) \cdot \pi R^2 = \sigma \varepsilon T^4 \, 4\pi R^2$ *Fast Rotator* w. uniform surface temperature.
L_{SUN} = 1360 W m^{-2} at 1 AU.
σ = Stefan-Boltzmann constant = 5.67e-8 W m^{-2} K^{-4}

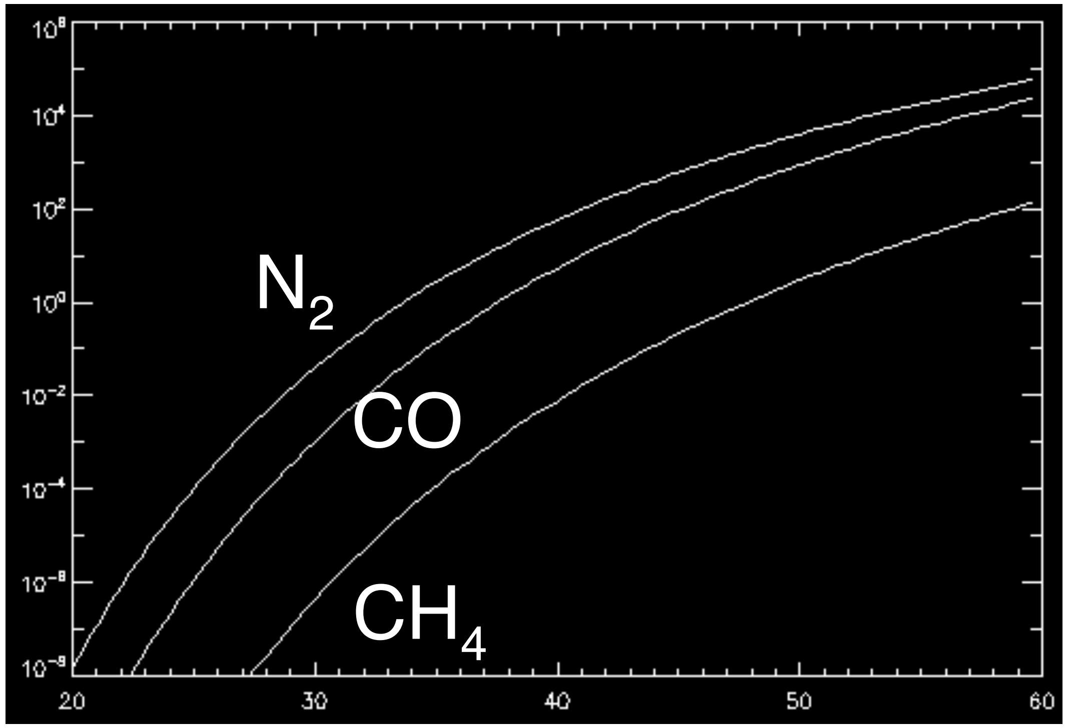
The Importance of Surface Temperatures

For surfaces covered with frosts, the surface pressure is a steep function of temperature.

The column abundance is roughly equal to the surface pressure over the surface gravity (approximate because *g* decreases with altitude). To first order, small changes in surface temperatures lead to huge changes in an object's bulk atmospheric abundance.

In nitrogen frost, every increase of 1.5 K results in a DOUBLING of vapor pressure.

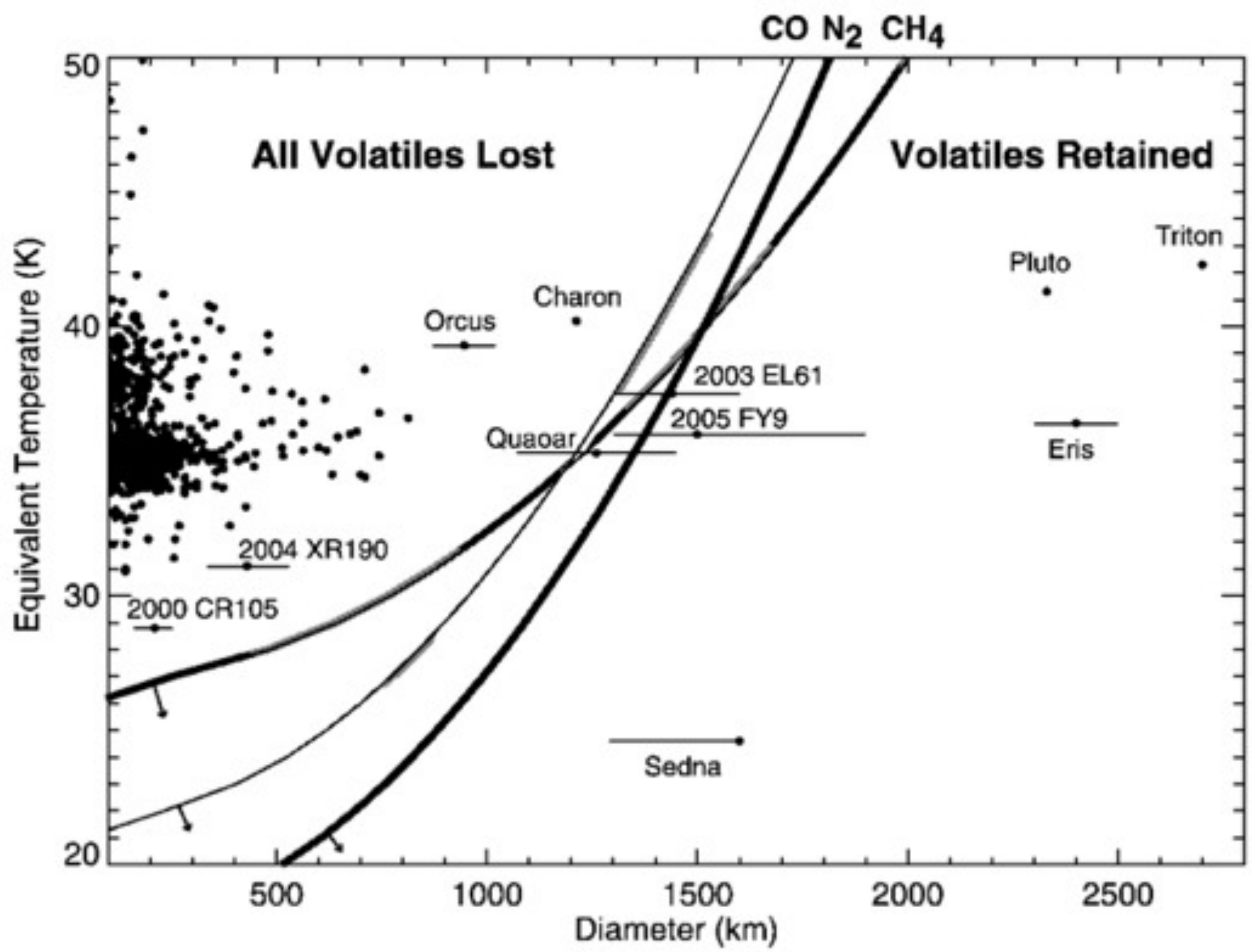
Other points:
- N2 and CO frosts are *much* more volatile than CH4 frost.
- Water ice is as volatile as rock at these temperatures.



Temp (K)	N_2 (µbar)	CO (µbar)	CH_4 (µbar)
20	1.45E-08	4.48E-11	1.62E-15
30	0.0393	0.00105	4.31E-07
40	57.7509	5.39328	0.00789
50	3956.30	875.003	2.94451
60	63314.9	24868.3	152.694

Expectations for TNOs?

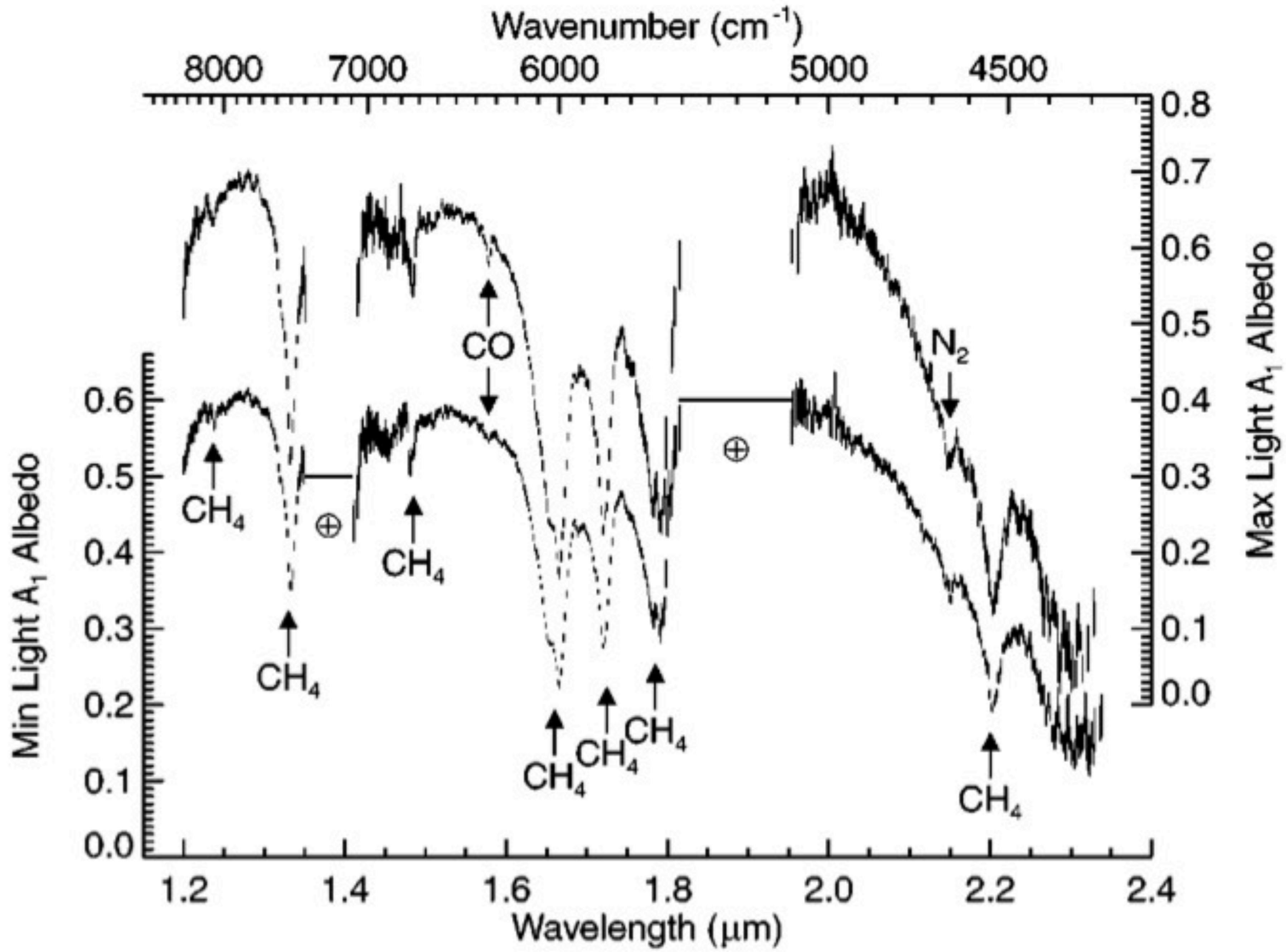
- Only the very largest TNOs should have atmospheres – small/warm TNOs have lost N_2, CO, CH_4 (e.g., Schaller & Brown 2007, *right*). Rule of thumb: V_{esc} should be more than 5x the peak of the Maxwell velocity distribution, V_{max} = sqrt(2*kT*/*m*).



- For most solar system objects, *water* is not a volatile. Very low surface pressure.
- Occultations should be more sensitive to the presence of volatiles than spectroscopy of the surface ices, especially for faint objects.

Known Frost Compositions

What surface frosts have been identified on Pluto, Triton, Eris, etc?



Surface frosts identified on Pluto: N2, CO and CH4 (Grundy & Buie 2001).

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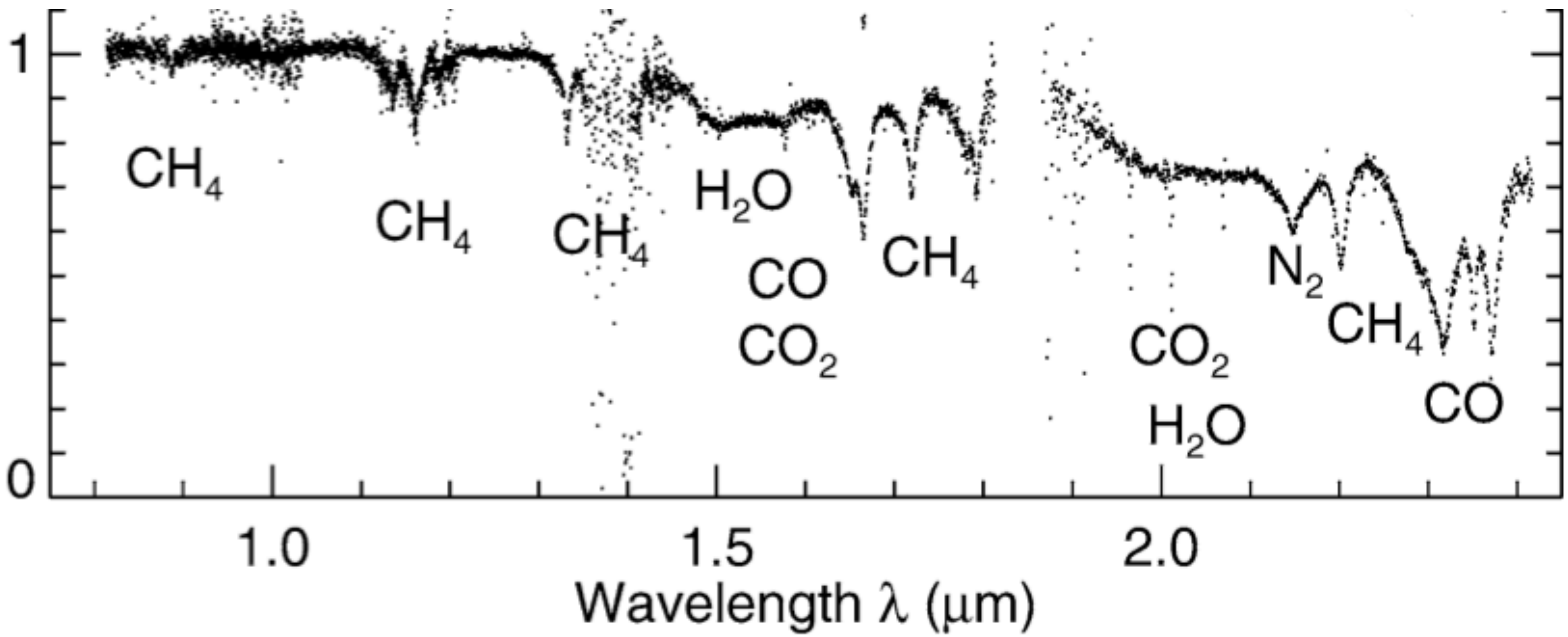

Surface frosts identified on Triton: N2, CO, CO2, H2O and CH4 (Grundy & Young 2004).

Known Frost Compositions

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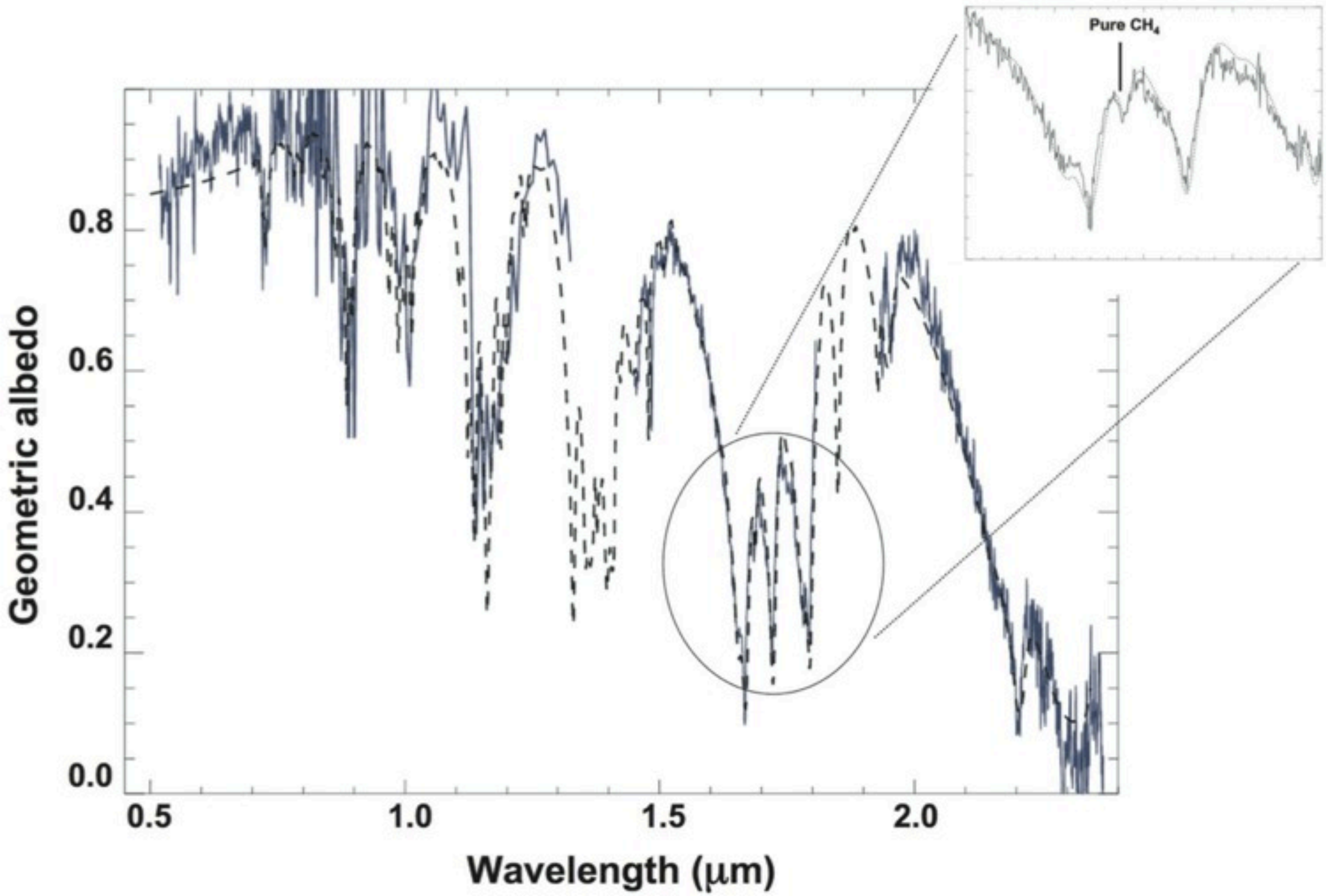


Surface frosts identified on Eris: CH4 (Dumas et al. 2007) with N2 inferred.

Nitrogen Ice on Eris?

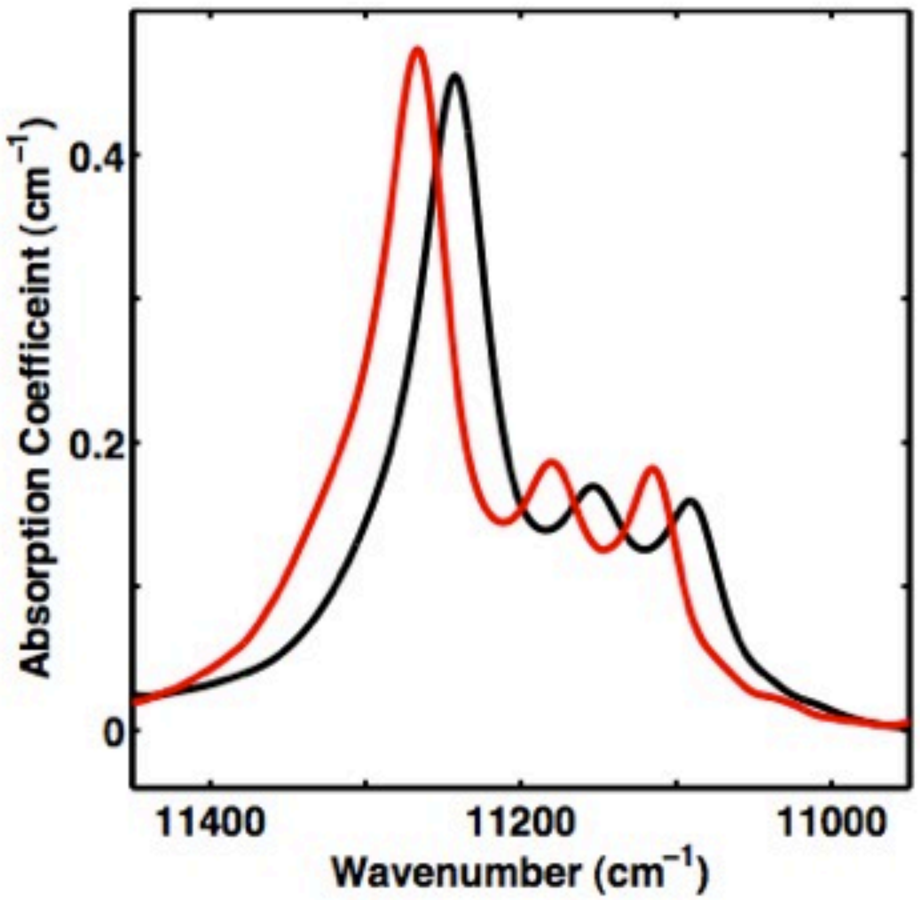


Fig. 3.— The 11240 cm^{-1} (8897 Å) band in the spectrum of a pure methane ice sample (black line). The same band in the spectrum of a sample of 6% methane and 94% nitrogen (red line). The band corresponding to the highly diluted methane sample (red line) has the same shape as the band corresponding to the pure sample (black line), but it is blue shifted by 26 cm^{-1} (21 Å).

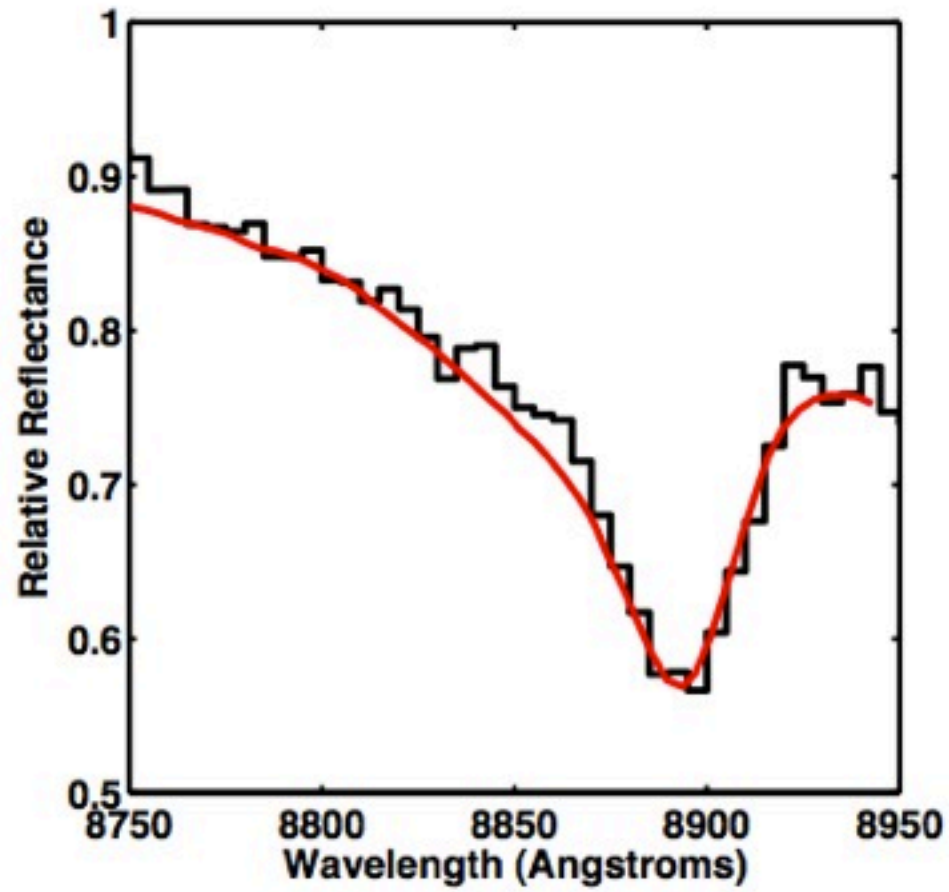
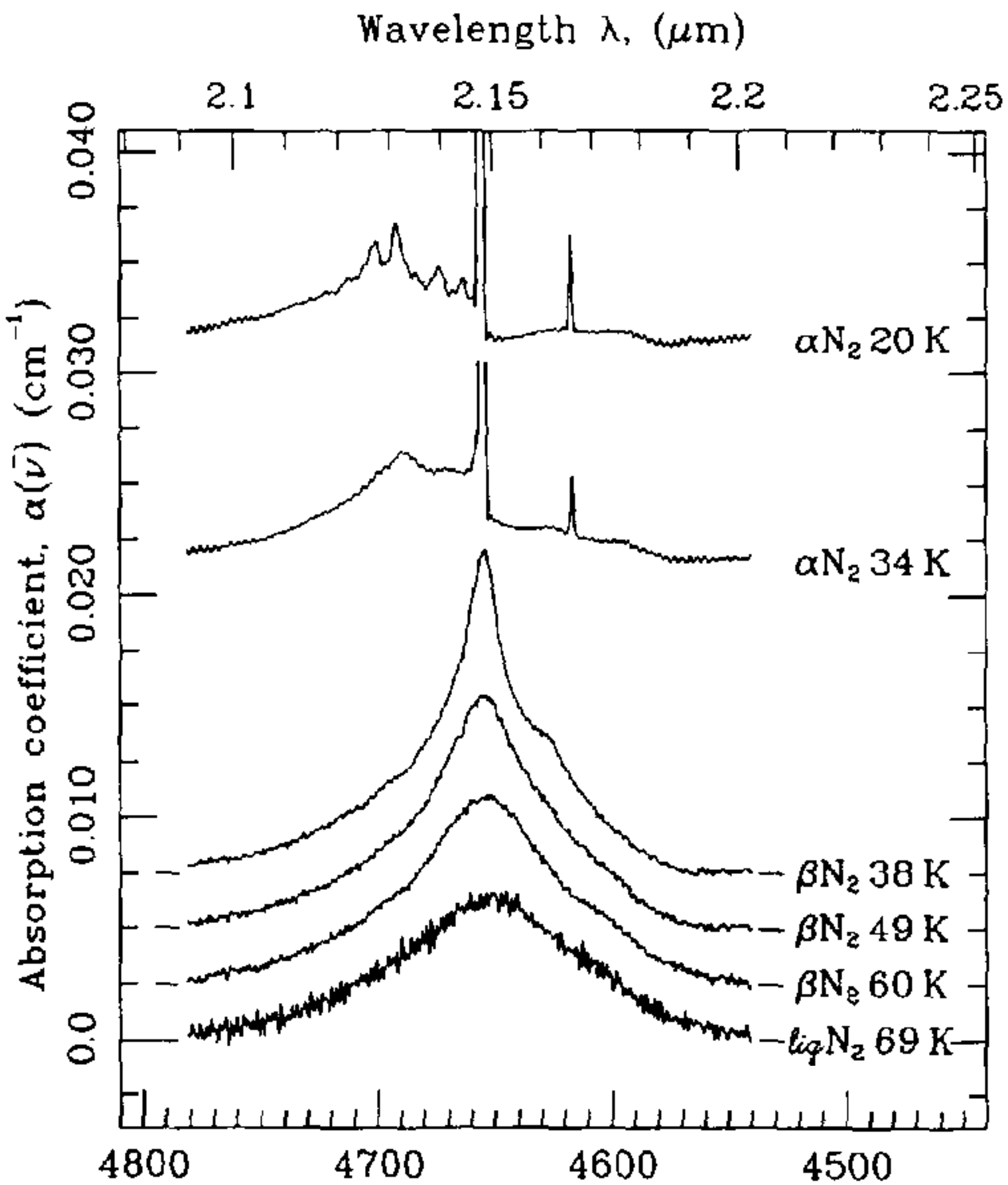


Fig. 9.— Eris' 8897 Å methane band taken on 2008 October 3 UT with the MMT 6.5 m telescope (black line), and the best fit pure methane Hapke model (red line). Blue shifting the pure methane band by 4.0 ± 0.6 Å gave the best fit to Eris' band. $\chi^2 = 10$

Methane frost in an N2 matrix shows shifted lines (e.g., Tegler et al. (2010)).

Nitrogen Ice as a Thermometer



The shape of a faint nitrogen ice feature has been used as a thermometer, yields a surface pressure estimate. Useful in conjunction with occultation pressure estimates.

Obviously a challenge requiring good quality spectra...

Vapor Pressure vs. Temperature: Implications

The fact that frost vapor pressures are steep functions of temperature has surprising implications.

Implication #1: The bulk atmospheric of an icy body can change dramatically if the frost temperature changes. Example: martian seasonal pressures.

Implication #2: If the latent heat of sublimation is an important energy term (compared to local solar heating, for example), then the global frost temperature *should be uniform*. (Imagine the non-uniform scenario, where small frost temperature variations exist. What kind of pressure field would you expect?)

Implication #2 breaks down in two cases: where the heat of sublimation is a minor term (Mars) or where the atmosphere is so thin (Io) that even supersonic winds can't balance pressure gradients.

Thought Exp. #1: Change in Pluto's Atmosphere

1989: Pluto's distance from the Sun is 29.7 AU
2012: Pluto's distance from the Sun is 32.2 AU

Question: by what fraction has Pluto's atmosphere decreased over that period? (Alternatively, what drop in temperature do we expect?)

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Step 1: What is the change in Pluto's surface temperature?

Recall: $L_{SUN} \cdot (1\text{-Albedo}) \cdot \pi R^2 = \sigma\varepsilon T^4 \, 4\pi R^2$

so $T = [(L_{SUN} \cdot (1\text{-Albedo}))/(4\sigma\varepsilon)]^{1/4}$

If L_{SUN} decreases by 17% (check it!), then T decreases by about 4%.

If T(1989) was 42 K, then T(2012) should be about 40.4 K.

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so $T = [(L_{SUN} \cdot (1\text{-Albedo}))/(4\sigma\varepsilon)]^{1/4}$

If L_{SUN} decreases by 15% (check it!), then T decreases by about 4%.

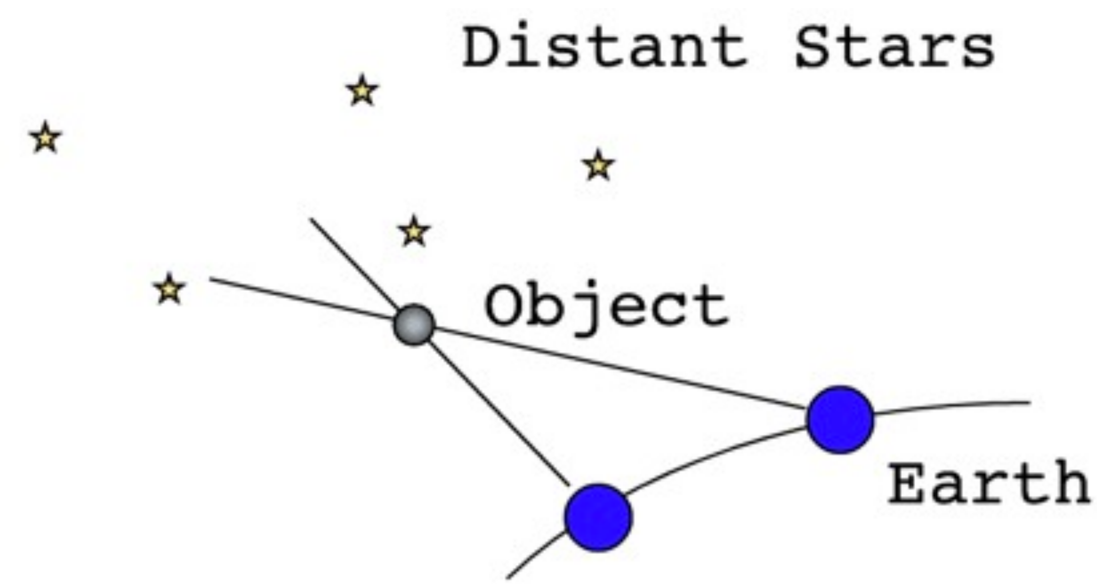
If T(1989) was 42 K, then T(2012) should be about 40.4 K.

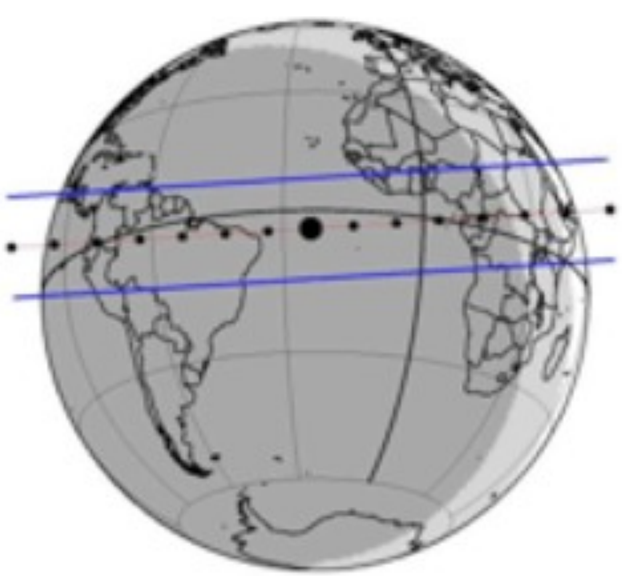
Step 2: For N2 frost, P(42K) = 159 µbar, P(40.4K) = 71 µbar.

Sunday, August 5, 2012

Aside into Occultations

For solar system bodies, stellar occultations occur when an object's parallactic motion intersects a star. *Typically velocity on the sky plane at 30-40 AU: ~20 km/sec*

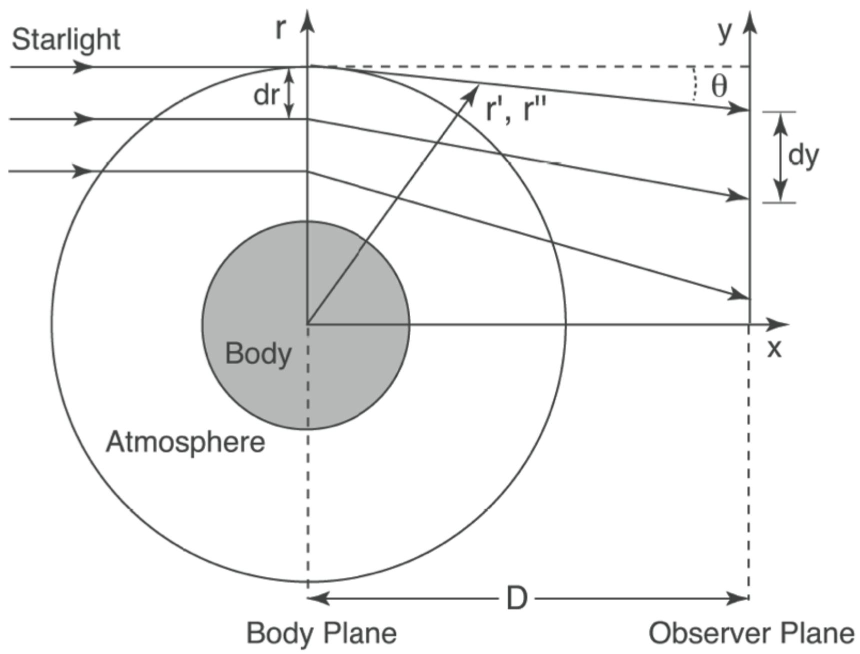




Part of the challenge is predicting the exact location of the shadow path. *An error in astrometry of 10 mas translates to about 200 miles on the Earth.*

The *width* of the shadow path is the width of the occulting object, about 2400 km in the case of Eris (NY to Las Vegas).

Aside into Occultations



1092 PETERSON *ET AL.*: LUNAR OCCULTATIONS OF HYADES 1092

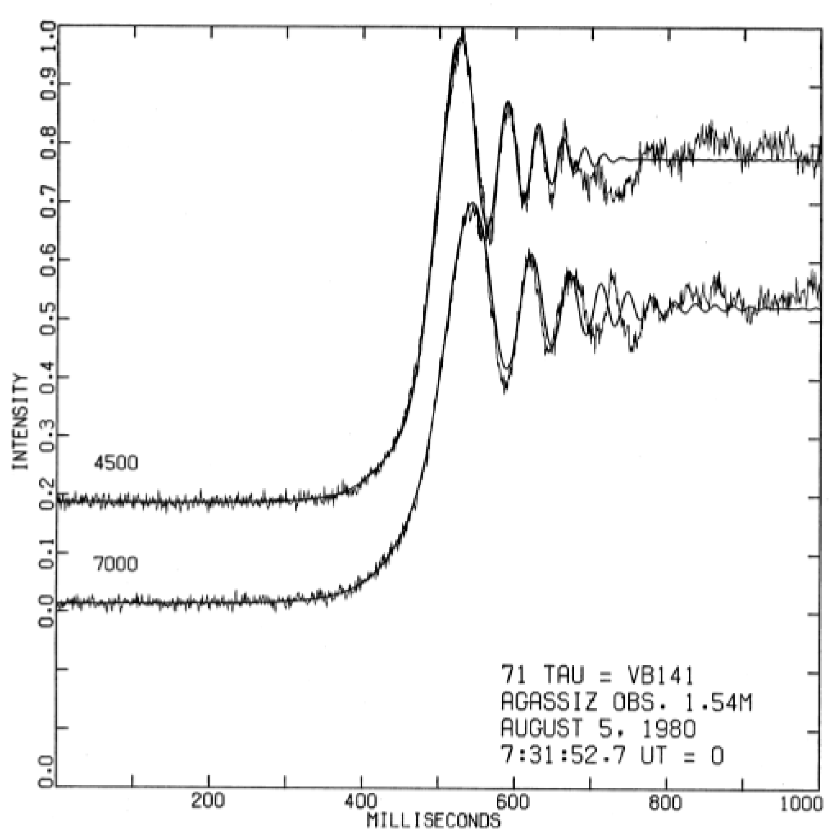


FIG. 1(a). The emersion of 71 Tau observed at Agassiz. The two curves are labeled by the approximate filter wavelenths. This figure shows the fit with both secondary and primary objects. Note the limb distortion effects at 700 ms.

Occultations are extremely sensitive to the presence of an atmosphere. Reason: small deflections in ray angle translate to large excursions over 30 or 40 AU.

Expect diffraction patterns in the ***no-atmosphere*** *case. Expect differential refraction in the presence of an atmosphere.*

Diffraction patterns are important diagnostic signatures for small TNO discovery programs.

Aside into Occultations

JOURNAL DES OBSERVATEURS

FONDÉ PAR HENRY BOURGET

PARAISSANT LE 15 DE CHAQUE MOIS

Volume XII — N° 1. — *15 Janvier 1929*

Le rôle des Atmosphères dans les Occultations par les planètes

par M. CH. FABRY

Membre de l'Institut, Professeur à la Sorbonne

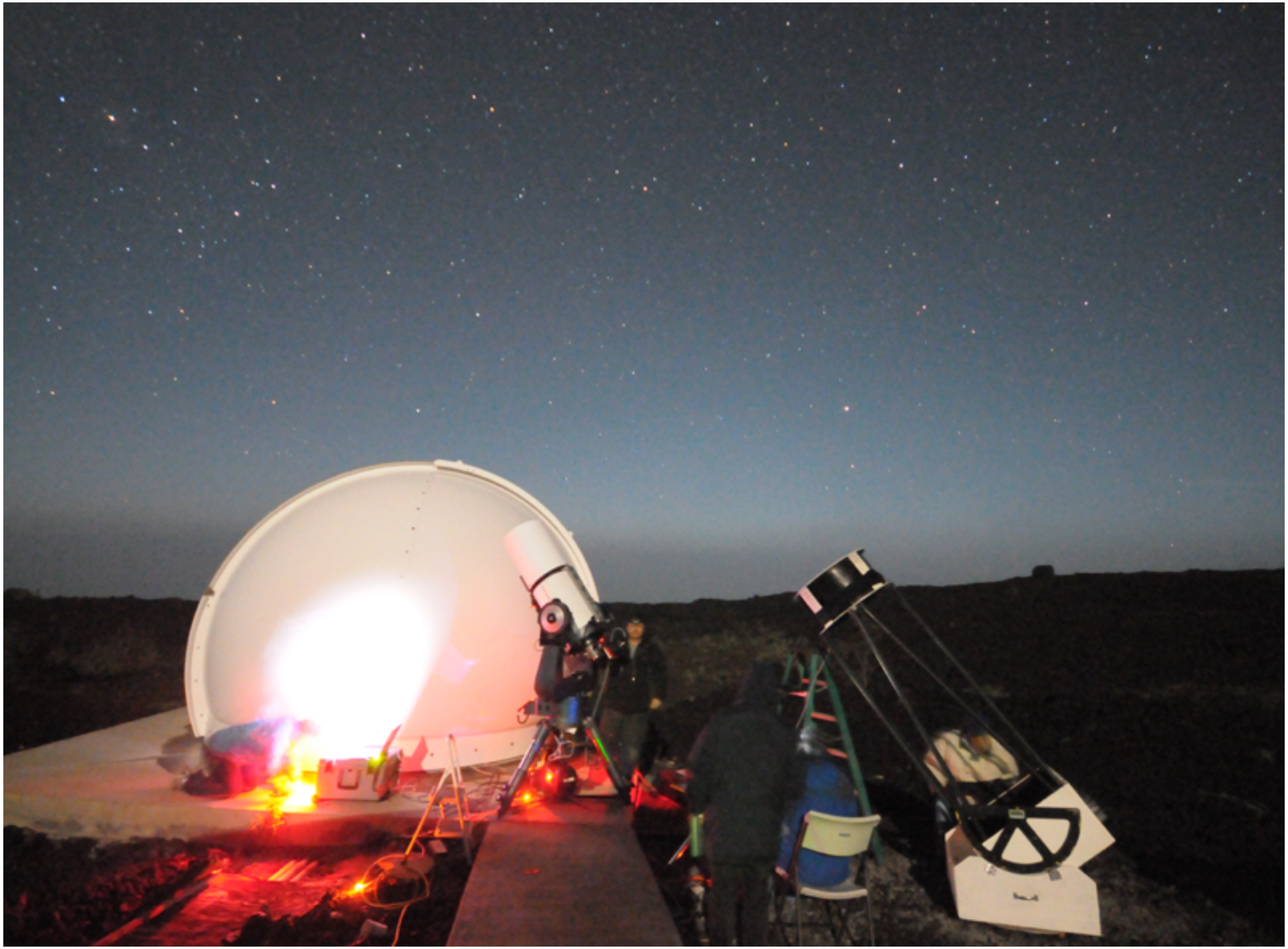
Sommaire. — Dans les occultations d'étoiles, l'atmosphère de l'astre occultant doit produire non seulement une déviation de l'étoile occultée, mais encore un affaiblissement considérable dû à la divergence des rayons par réfraction, indépendamment de toute absorption.

Après avoir établi les formules relatives à ces deux phénomènes, l'auteur discute les conditions de l'occultation par les diverses planètes et par la lune. Il étudie ensuite le cas où l'astre occulté a un diamètre apparent sensible. Il indique enfin les conditions les plus favorables à l'observation des phénomènes prévus par la théorie.

Aside into Occultations

Occultation campaigns take you to interesting places...

Aside into Occultations

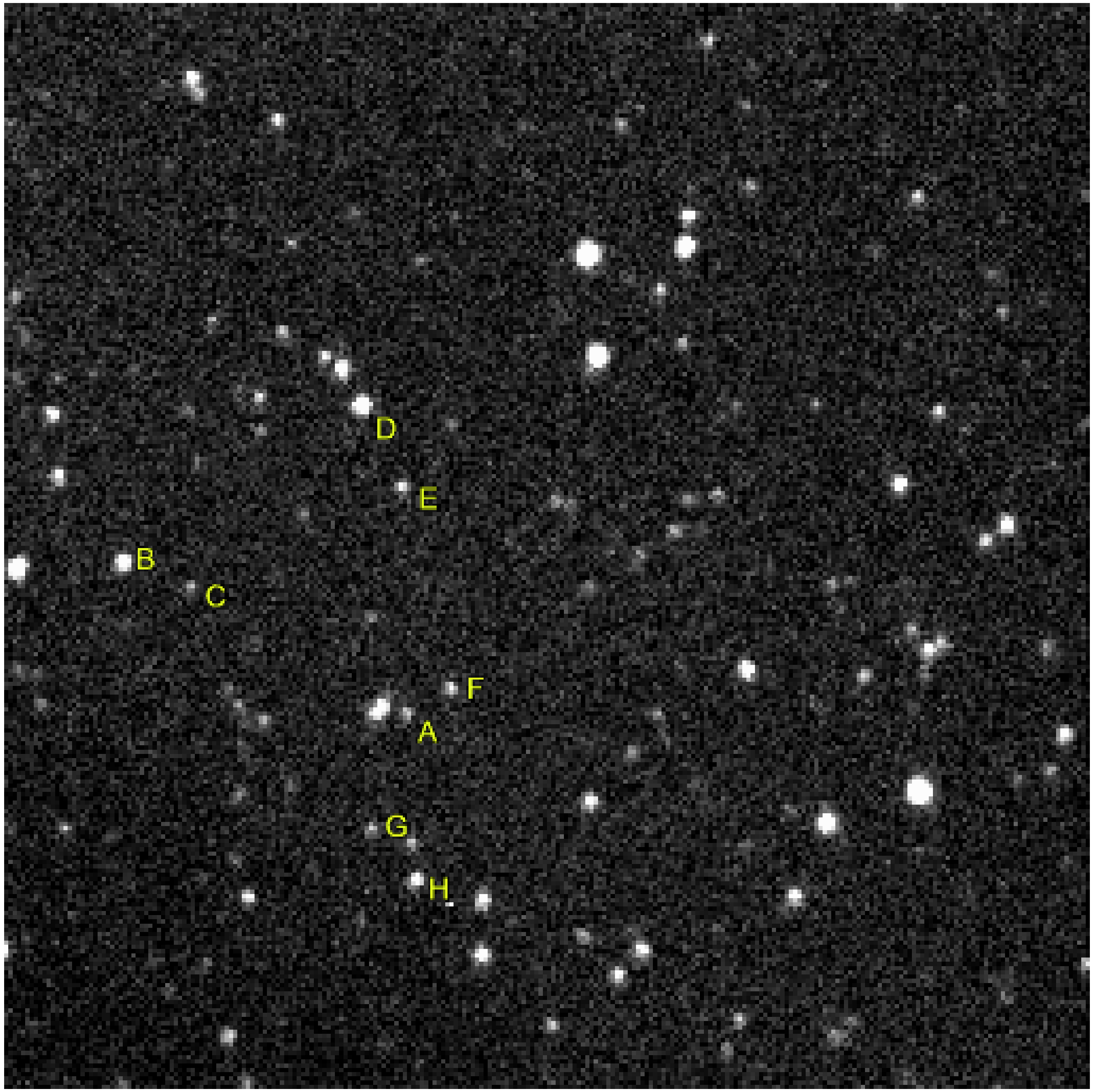


Occultation campaigns take you to interesting places...

Pluto Occultations

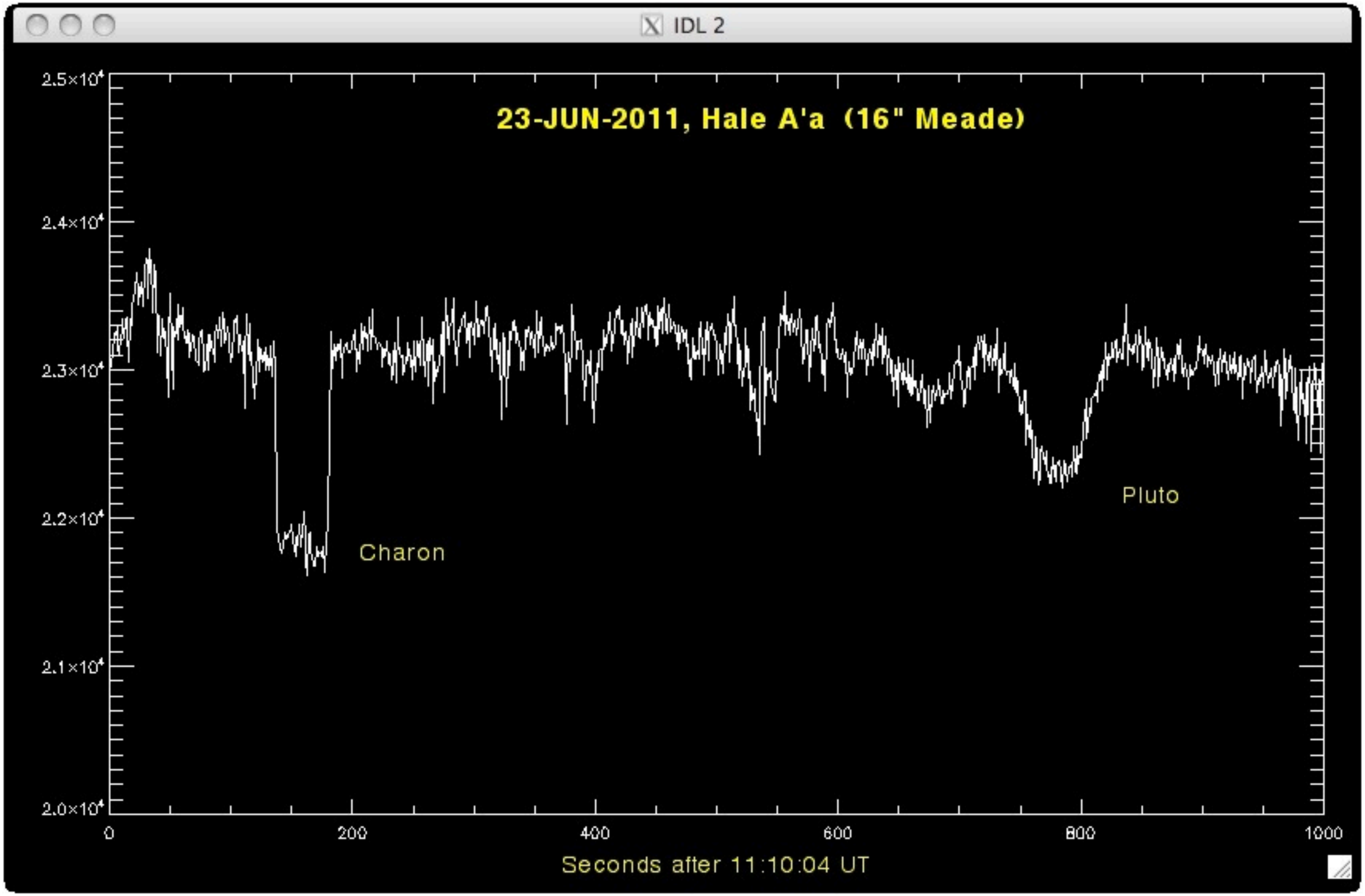
A typical occultation frame.

"A" is the star to be occulted. Differential photometry is important.



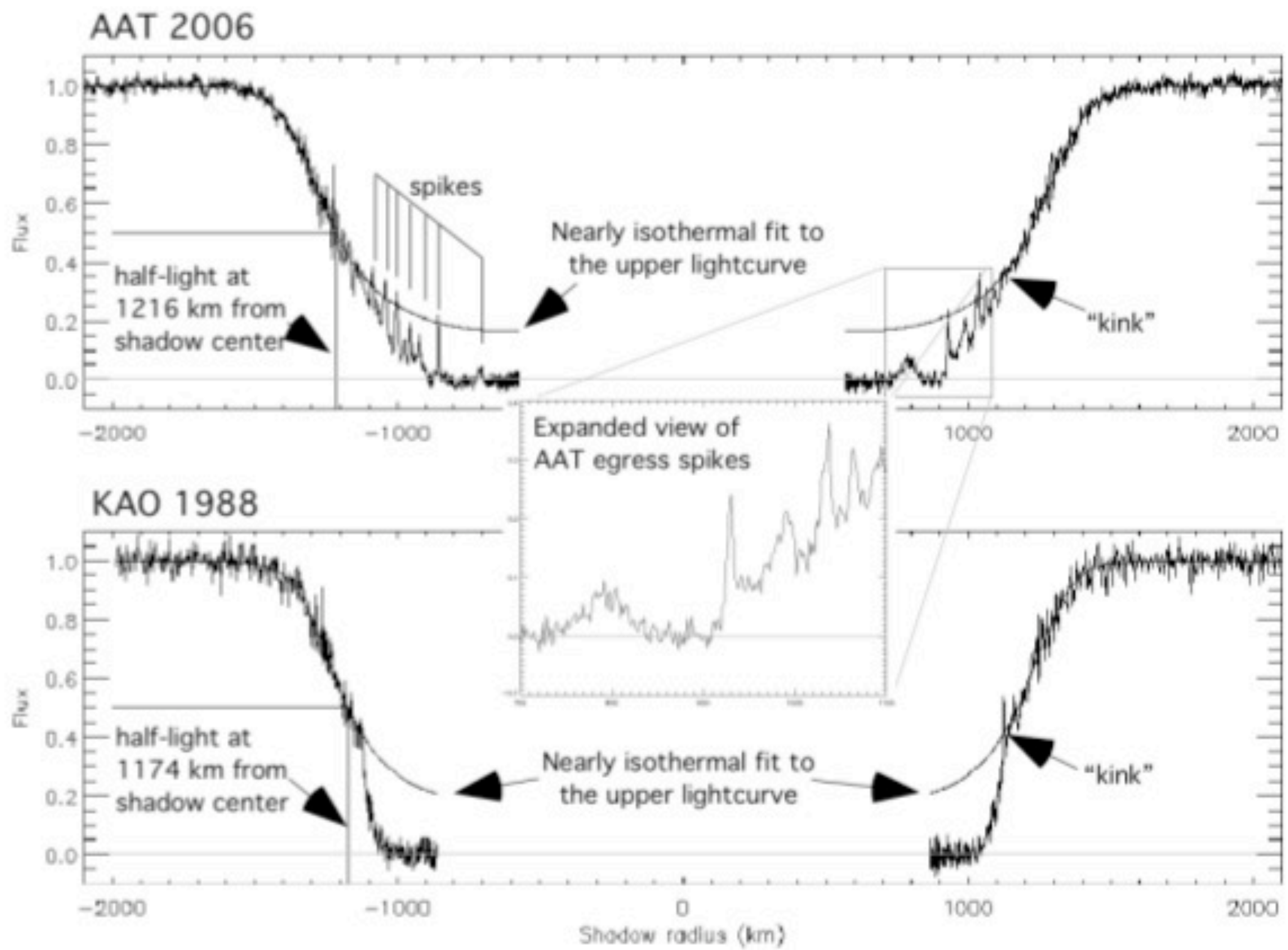
12-JUL-2006 Pluto Occultation (14" Meade)

Pluto Occultations



June 23, 2011, Hale A'a (16" Meade)

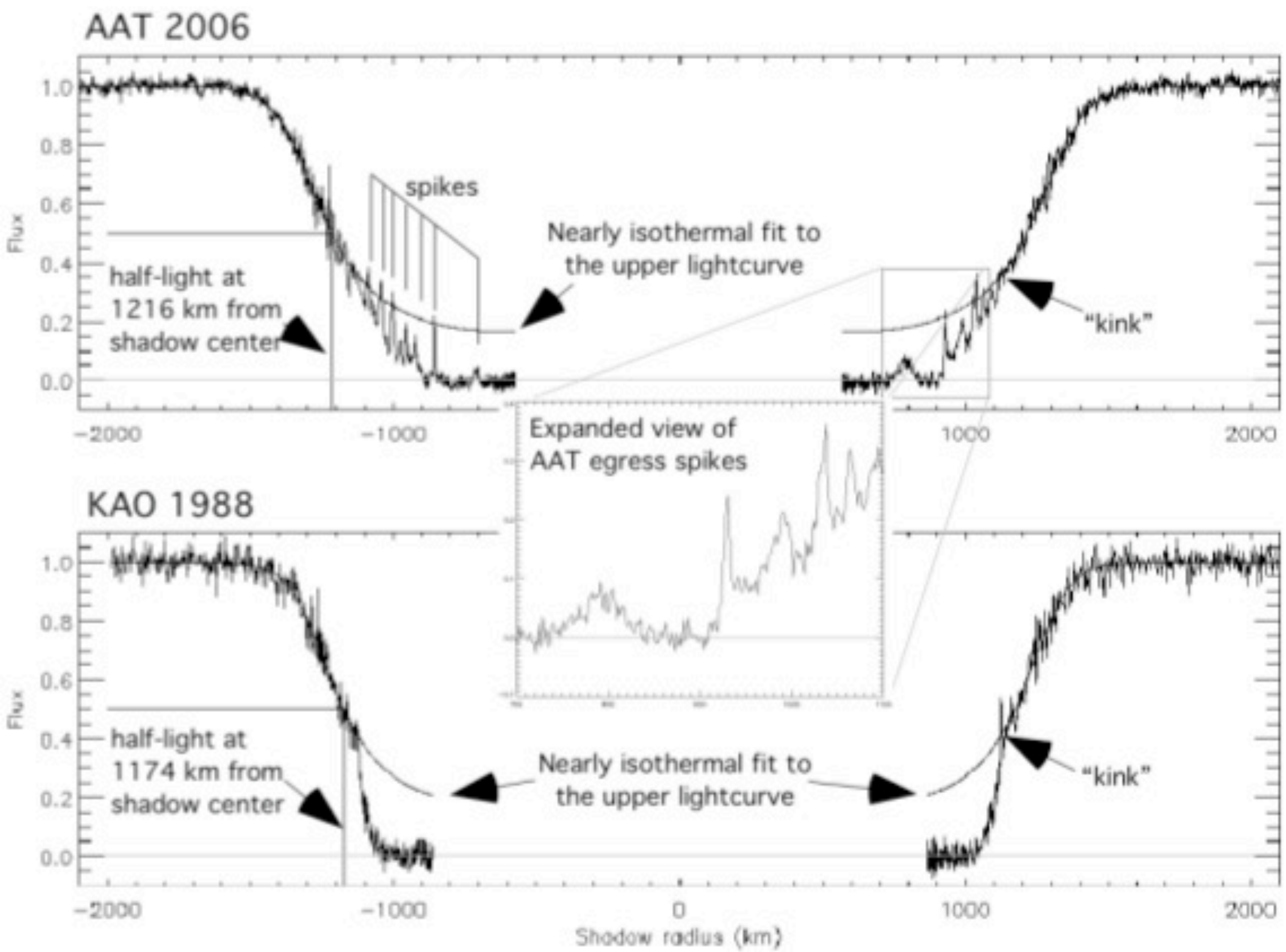
Pluto Occultations



When there *is* an atmosphere, the observed occultation lightcurve is a sensitive probe of

- Pressure & Temp. profiles (and changes with respect to time)
- Extinction (e.g., by haze, implied by the "kink in the lightcurve")
- Some dynamics (e.g. gravity waves, implied by spikes)

Pluto Occultations



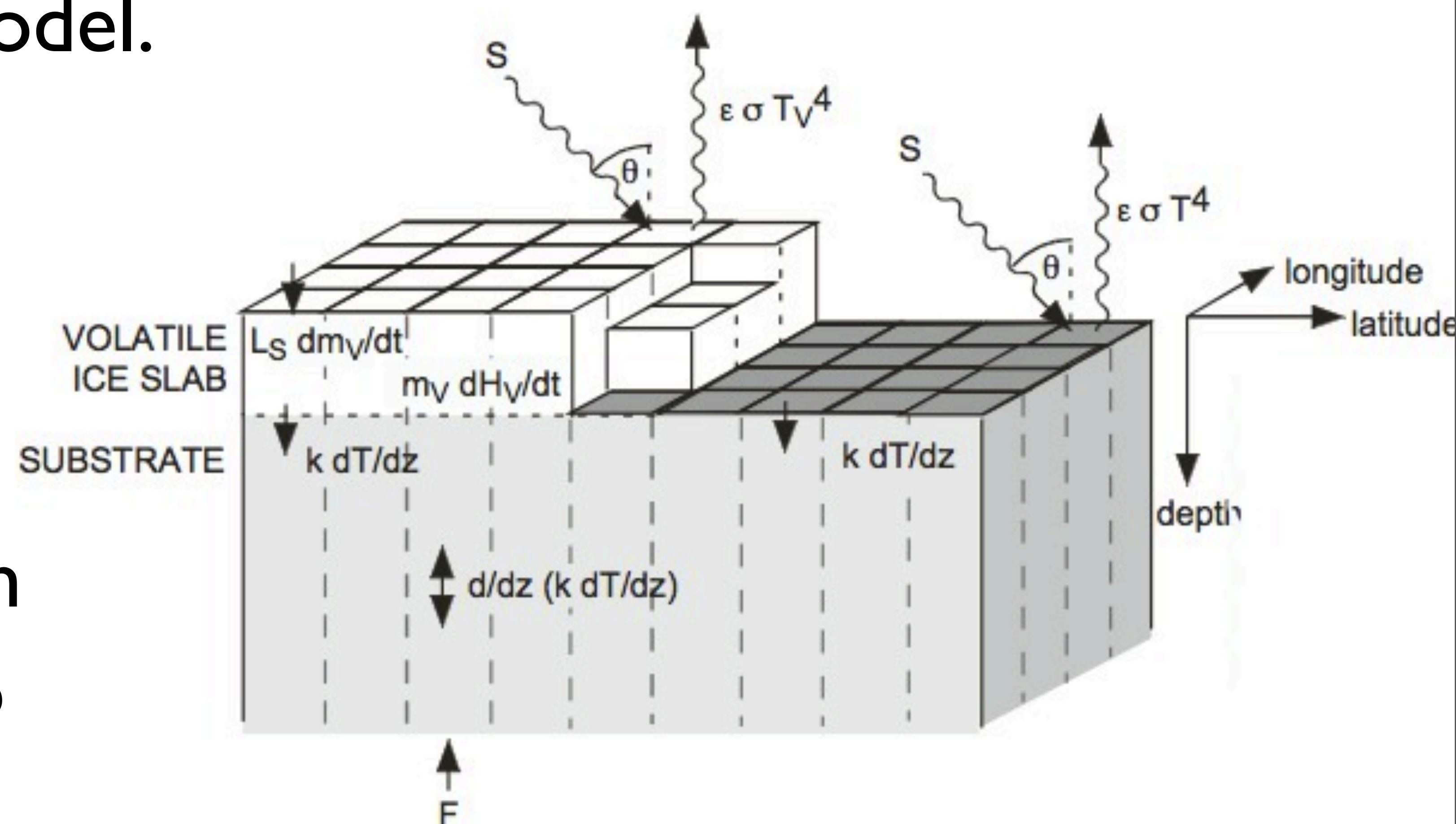
Note that the "half-light radius" increased from 1988 to 2006. Even though Pluto received about 10% less solar flux in 2006 than in 1988, its atmosphere *doubled* during that interval!

Question: Why the Increase in Pluto's Atm?

Short answer: thermal inertia of the subsurface.

On Earth, the warmest time of day is in the afternoon, even though the received solar energy peaks at noon.

We model the daily and seasonal surface–atmospheric coupling with a volatile transport model.



Energy transport terms:

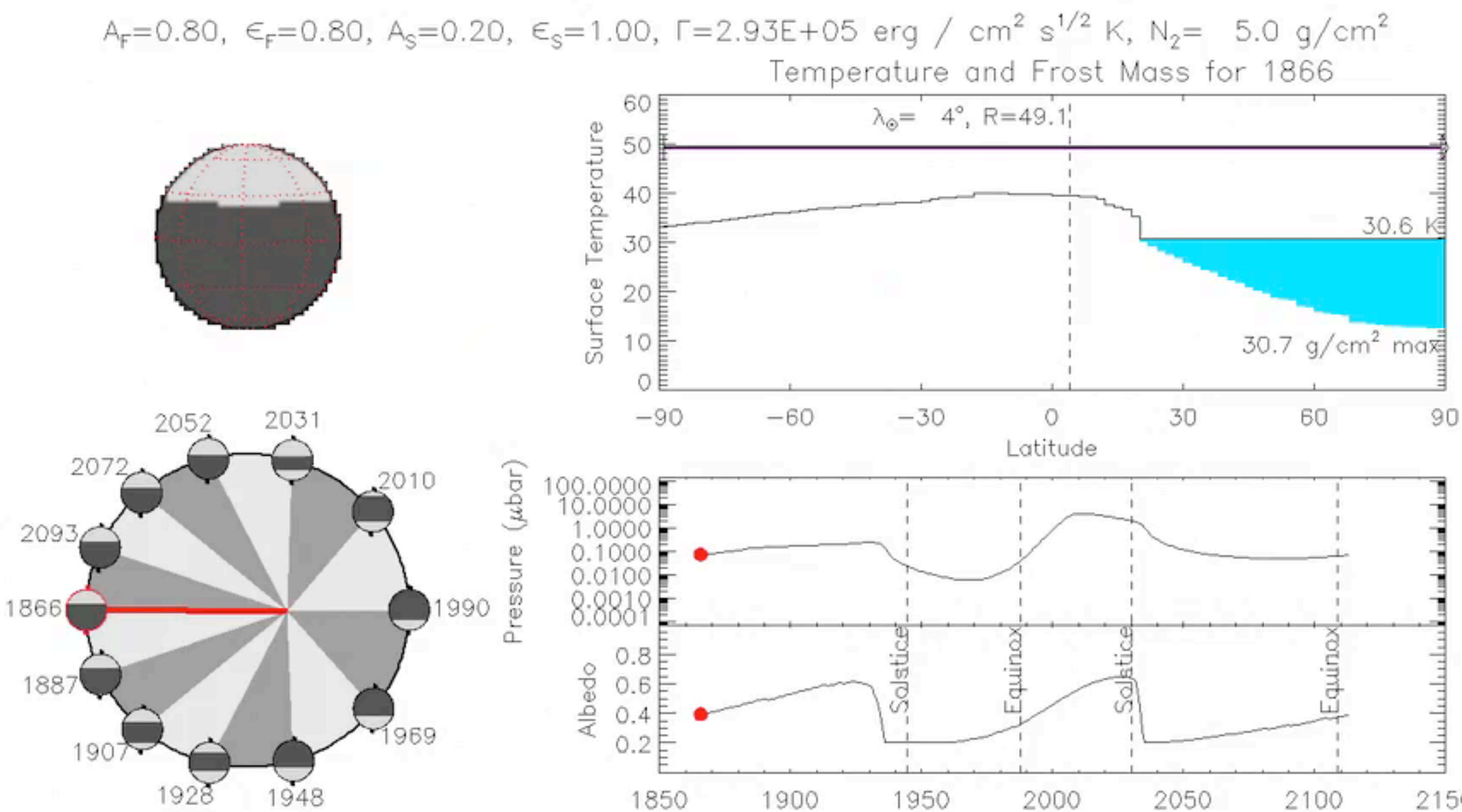
- Solar insolation
- Thermal radiation
- Latent heat of sublimation
- Conduction from frost to substrate
- Conduction within the substrate

Volatile Transport

The energy stored in the latent heat of sublimation and especially in the thermal wave that propagates into the surface serve to decrease the amplitude of the surface frost's temperature variations.

A Year on Pluto

- Prediction #1: Not all latitudes are covered in frost
- Prediction #2: Pressure peaks decades AFTER perihelion
- Prediction #3: Sudden changes in albedo and pressure



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Occultations: Sensing Very Thin Atmospheres

Limitations of current occultation modeling tools (e.g., Elliot and Young, "Analysis of Stellar Occultation Data..." 1992; Sicardy et al., "The structure of Titan's atm..."; 1999; Roques et al. "Stellar Occultations by Small Bodies: Diffraction Effects 1997) include:

- The ability to model *diffraction* or *refraction*, but not a combination of the two (which might be important for thin atmospheres).
- The ability to model *hazes* within clear atmospheres.
- The ability to model local atmospheric perturbations and oddly-shaped planets.

We now present a Fourier Optics-based modeling approach...

Occultation Models: A Fourier Optics Approach

I have then shown in what manner one may conceive Light to spread successively, by spherical waves, and how it is possible that this spreading is accomplished with as great a velocity as that which experiments and celestial observations demand...

But what may at first appear full strange and even incredible is that the undulations produced by such small movements and corpuscles, should spread to such immense distances; as for example from the Sun or from the Stars to us.

Christiaan Huygens, 1690
Treatise on Light
(http://www.gutenberg.org/etext/14725)

- BASIC IDEA: Treat the aperture plane as a 2-dimensional array of spherical wavelets.
- The phase and amplitude of a traveling spherical wave: $E(r,t) = \left(\frac{A}{r}\right) e^{i(kr-\omega t)}$
- Direct summation of complex wavefronts in the observer's plane is very expensive - you need to sample planet-size apertures on a wavelength-size grid.

Closed-Form Solution

Problem: How to evaluate the 2-D integral that sums over spherical wavelets? (Ref: Goodman, *Introduction to Fourier Optics*)

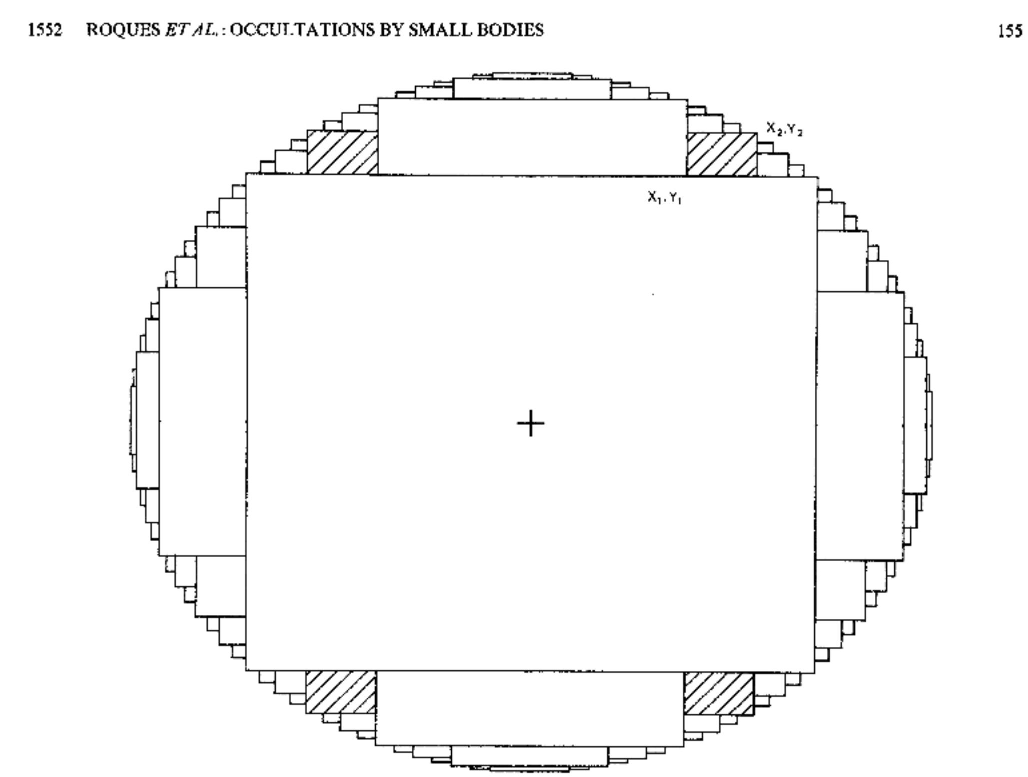
$$E_{obs}(x_1, y_1) = \left(\frac{-i}{\lambda}\right) \iint_{-\infty}^{\infty} E_{ap}(x_0, y_0) A(x_0, y_0) \frac{e^{ikr}}{r} dx_0 dy_0$$

where E_{obs} and E_{ap} are complex electrical fields in the observer's and aperture plane, A is the opacity function in the aperture plane, k is the wavenumber ($k = 2\pi/\lambda$), and r is the distance between points in the aperture plane (x_0, y_0) and the observer's plane (x_1, y_1).

Some solutions for special geometries...

Roques, Moncuquet & Sicardy (1987) evaluate the integral for RECTANGULAR cases, which requires evaluations of the Fresnel function, $F(x) = \int_0^x \frac{i\pi}{e^2} X^2 dX$

$$E_{obs}(x_1, y_1) = 1 - N\lambda \left[F(x_L - x) - F(x_R - x)\right] \times \left[F(y_L - y) - F(y_R - y)\right]$$



- Dubra and Ferrari (1998) transform to a polar coordinate to get a 1-D integral (albeit with unusual bounds of integration)

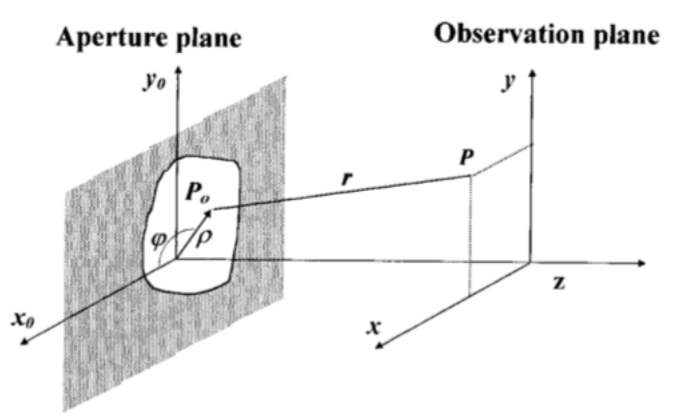


Fig. 1. Illustration of the coordinate system utilized to solve Rayleigh–Sommerfeld's integral.

Closed-Form Solution

In Goodman's book, *U(x,y,0)* is the complex E-field in the aperture plane and $A_0(f_x, f_y)$ is the angular spectrum (Fourier transform) of *U*.

$$A_0(f_x, f_y) = \iint_{-\infty}^{\infty} U(x, y, 0) e^{-i2\pi(f_x x + f_y y)} dx dy$$

Let $t(x, y)$ be the aperture's transmittance function and $T(f_x, f_y)$ be its angular spectrum. The E-field immediately following the aperture is $U(x,y,0) \cdot t(x, y)$. If the incident E-field is a plane wave, then the angular spectrum of the emergent field is the Fourier transform of the aperture, $T(f_x, f_y)$.

Question: why would one bother transforming the E-field at the aperture into an angular spectrum?

Answer: Because the propagation phenomenon is a *convolution* in the spatial domain, or a *multiplication* in the frequency domain.

(See the section entitled "The propagation phenomenon as a linear filter" in Chapter 3 of Goodman.) The following transfer function transforms the angular spectrum of the E-field at the aperture plane into the E-field at the observer's plane.

$$H(f_x, f_y) = \frac{A(f_x, f_y; z)}{A(f_x, f_y; 0)} = e^{ikz\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}}$$

The Fresnel and Fraunhofer Regimes

The Fresnel regime: we seek the E-field where the distance between the aperture plane and the observer's plane is much greater than any lateral offsets within either plane.

$$z^3 >> \frac{\pi}{4\lambda}\left[(x_0 - x_1)^2 + (y_0 - y_1)^2\right]^2_{max}$$

The Fraunhofer regime assumes that the quadratic phase factor is approximately unity over the entire aperture.

$$z >> \frac{k(x_0^2+y_0^2)_{max}}{2}$$

For a case like Eris (z > 4.5e9 km, maximum Δ*x* and Δ*y* of about 5000 km, λ around 0.5 μm), the Fresnel condition is satisfied (by about 5 orders of magnitude) while the Fraunhofer condition is not.

That's too bad – the observer's plane E-field is the Fourier transform of the aperture in the Fraunhofer regime.

A Shortcut in the Fresnel Regime

If you are willing to work in the Fresnel regime, there is a very simple Fourier optics approach to calculating the E-field in the observer's plane, well described in Tester 1999*.

Begin with the Huygens-Fresnel principle.

$$E_{obs}(x_1, y_1) = \left(\frac{-i}{\lambda}\right) \iint_{-\infty}^{\infty} E_{ap}(x_0, y_0) A(x_0, y_0) \frac{e^{ikr}}{r} dx_0 dy_0$$

In the fraction exp(*ikr*)/*r*, replace *r* in the denominator with z. You can't do that in the exponent, however, but you *can* expand *r* in terms of aperture and observer's plane coordinates and keep only the first two terms of a binomial expansion.

$$r = z_0\{1 + [(x_0 - x)^2 + (y_0 - y)^2]/z_0^2\}^{1/2}$$

$$r \approx z_0 + [(x_0 - x)^2 + (y_0 - y)^2]/2z_0$$

In addition, it is useful to expand the quadratic terms in $r = z_0 + \ldots$

$$r \approx z_0 + \frac{x_1^2 + y_1^2}{2z_0} + \frac{x_0^2 + y_0^2}{2z_0} - \frac{x_0 x_1 + y_0 y_1}{z_0}$$

This expansion lets us recast the integrand at top into something that resembles a Fourier transform.

$$E(x_1, y_1) = C_2 \iint_{-\infty}^{\infty} \left[E(x_0, y_0) A(x_0, y_0) e^{(ik/2z)(x_0^2 + y_0^2)}\right] e^{(-ik/z)(x x_0 + y y_0)} dx_0 dy_0$$

where

$C_2 = (-i/\lambda z) \exp(ikz) \exp[(ik/2z)(x^2 + y^2)]$ (Note that C_2 only contains observer's plane terms.)

* *Computer-Simulated Fresnel Diffraction Using the Fourier Transform* by Seymour Trester in *Computing in Science and Engineering*, vol. 1, no. 5, pp. 77-83, Sep/Oct 1999.

A Shortcut in the Fresnel Regime

We now have an even simpler recipe for calculating the E-field in the observer's plane:

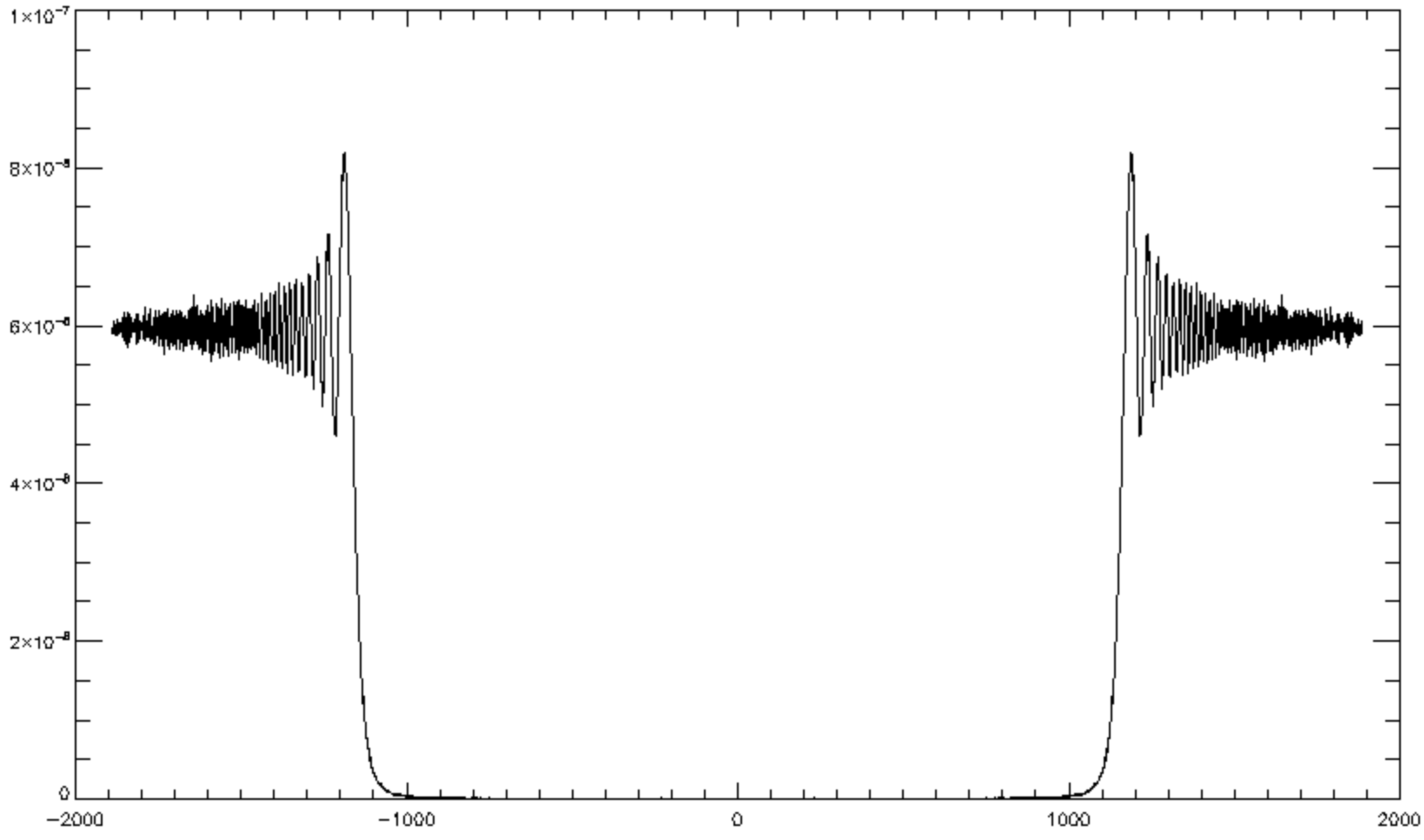
- Evaluate Trester's *modified aperture function, $M(x_0, y_0)$*.

$$M(x_0, y_0) = E_{ap}(x_0, y_0) A(x_0, y_0) e^{(ik/2z)(x_0^2 + y_0^2)}$$

- Take the Fourier transform of $M(x_0, y_0)$ and multiply by C_2 to get the E-field in the observer's plane
- The intensity in the observer's plane is the E-field times its complex conjugate. If you are only interested in the intensity, then you don't even have to evaluate C_2, which has an amplitude of one.
- We now have an easy way to model the lightcurves resulting from arbitrary atmospheres (haze layers, asymmetric) AND simultaneously model *diffraction* & *refraction* effects.

Transition from Diffraction to Refraction

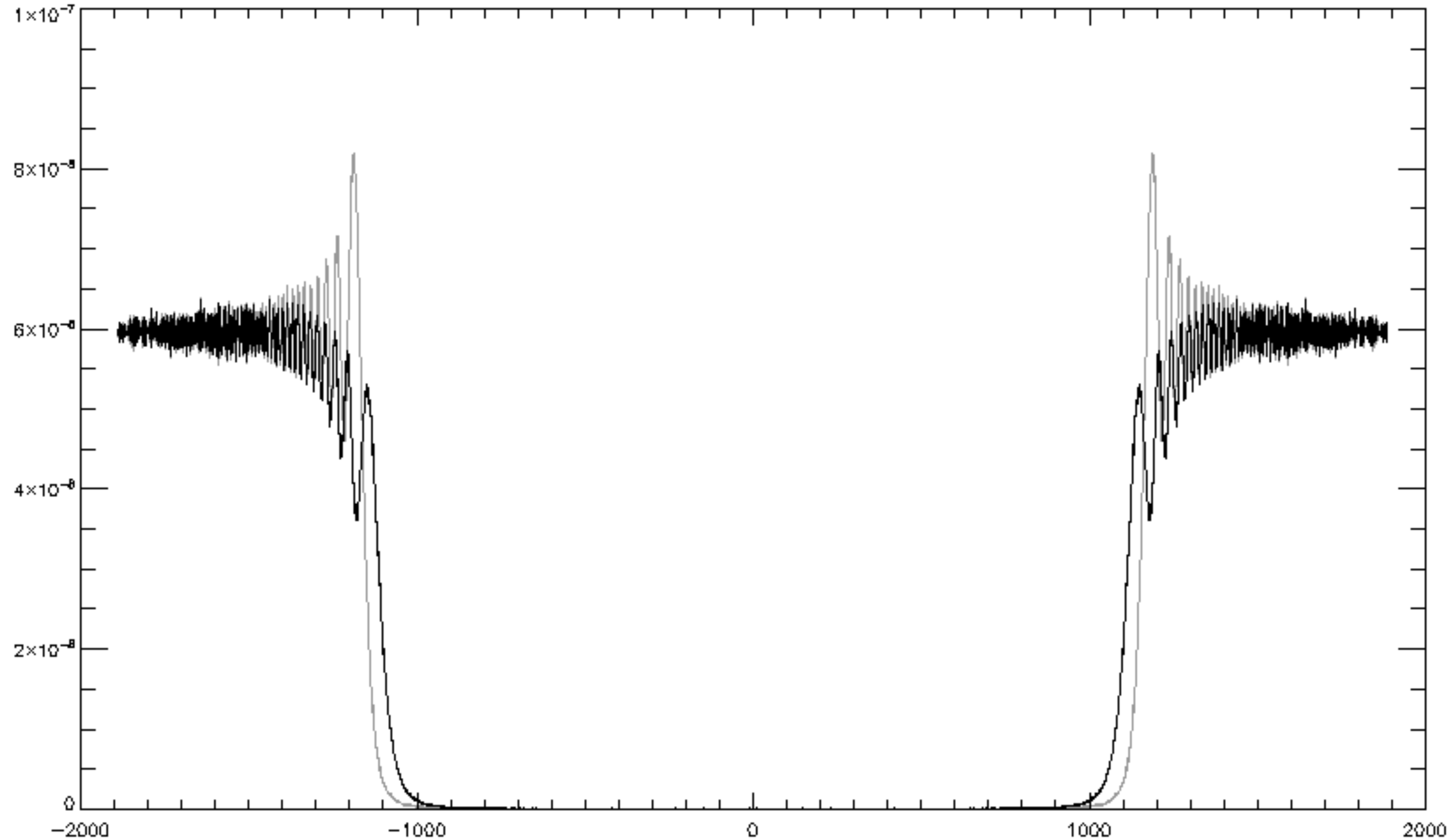
NO atmosphere



Question: How does the diffraction lightcurve change as we add very thin atmospheres?

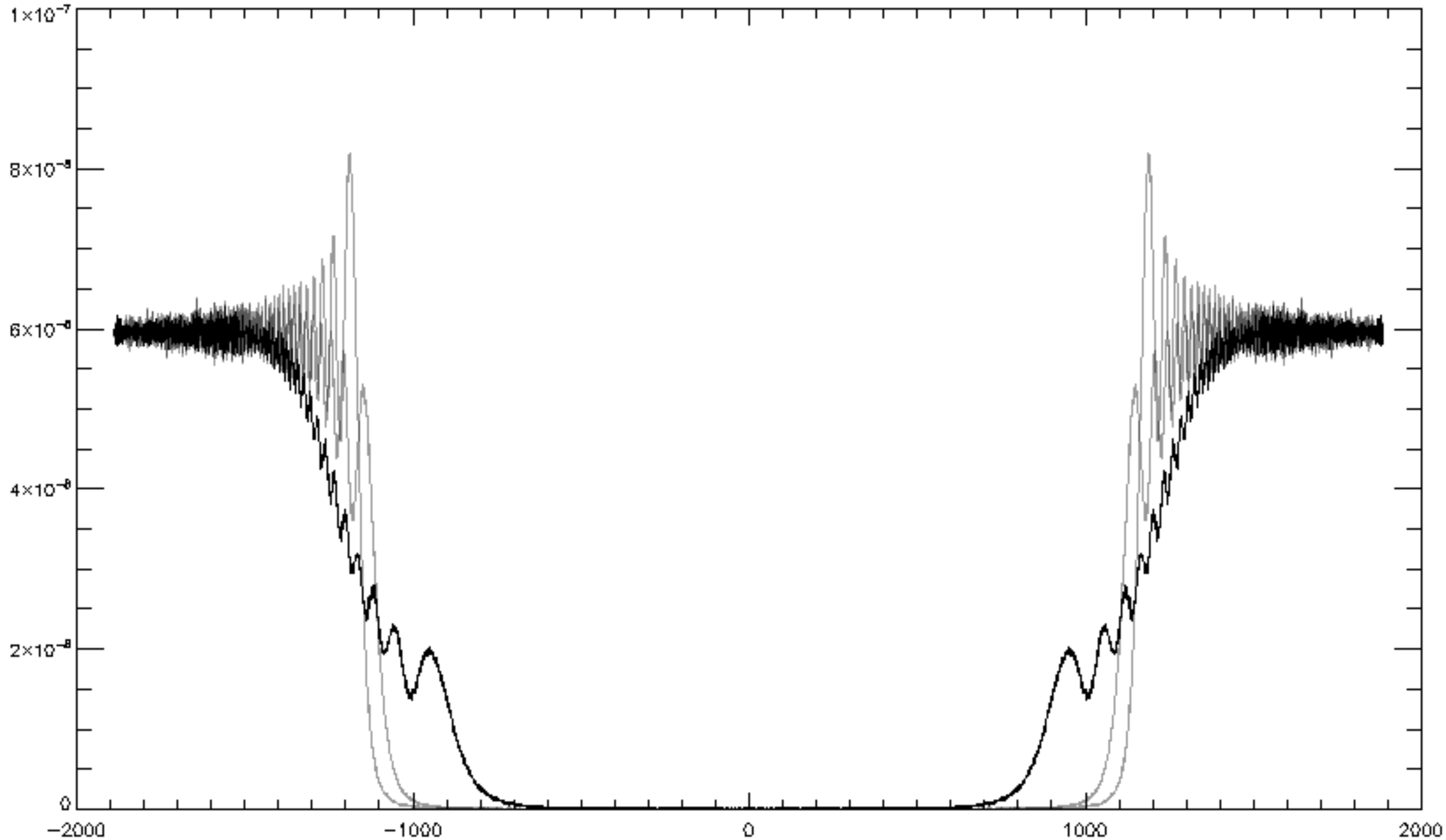
Transition from Diffraction to Refraction

0.1% of Pluto's Atmosphere



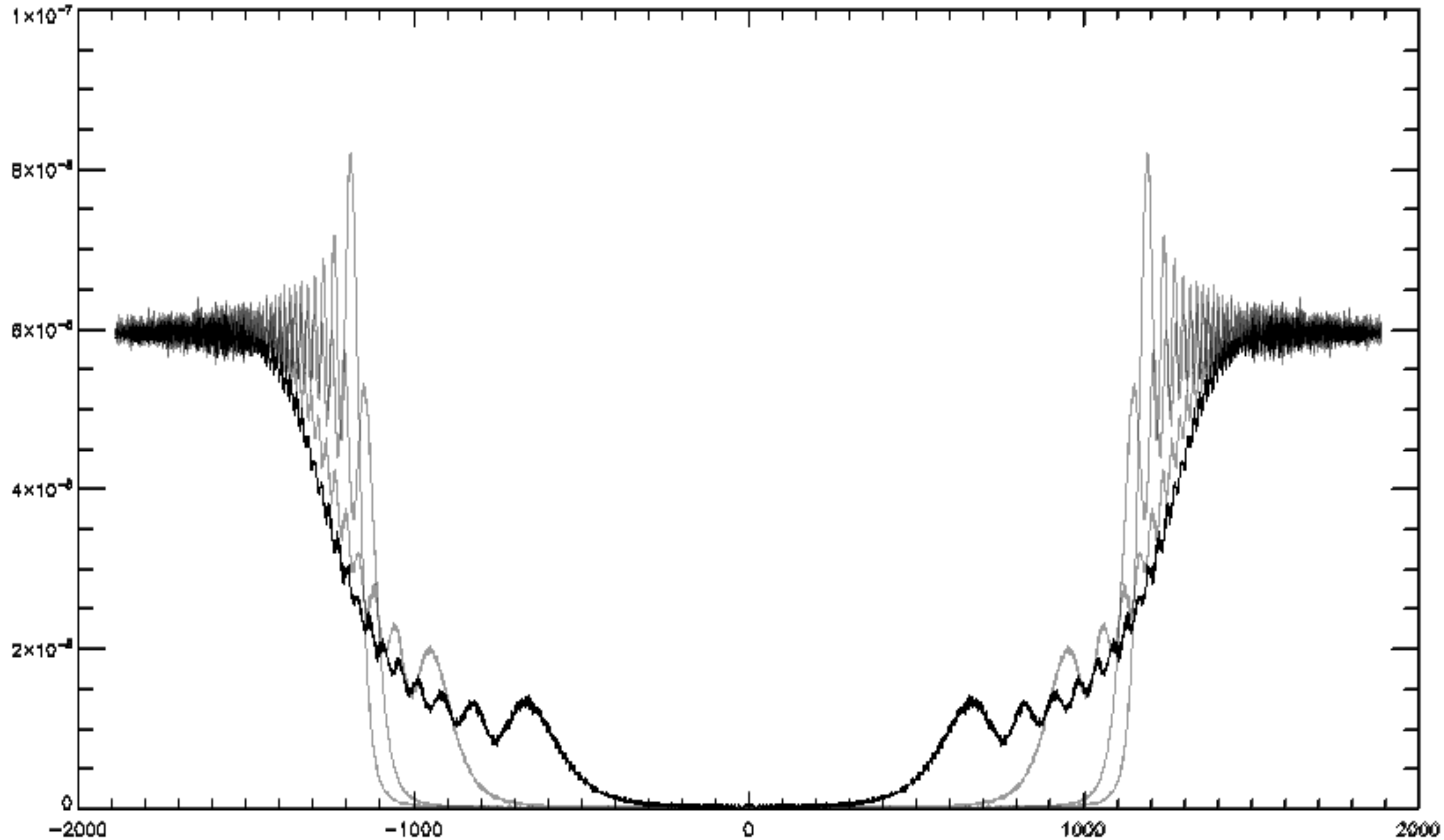
Transition from Diffraction to Refraction

0.2% of Pluto's Atmosphere



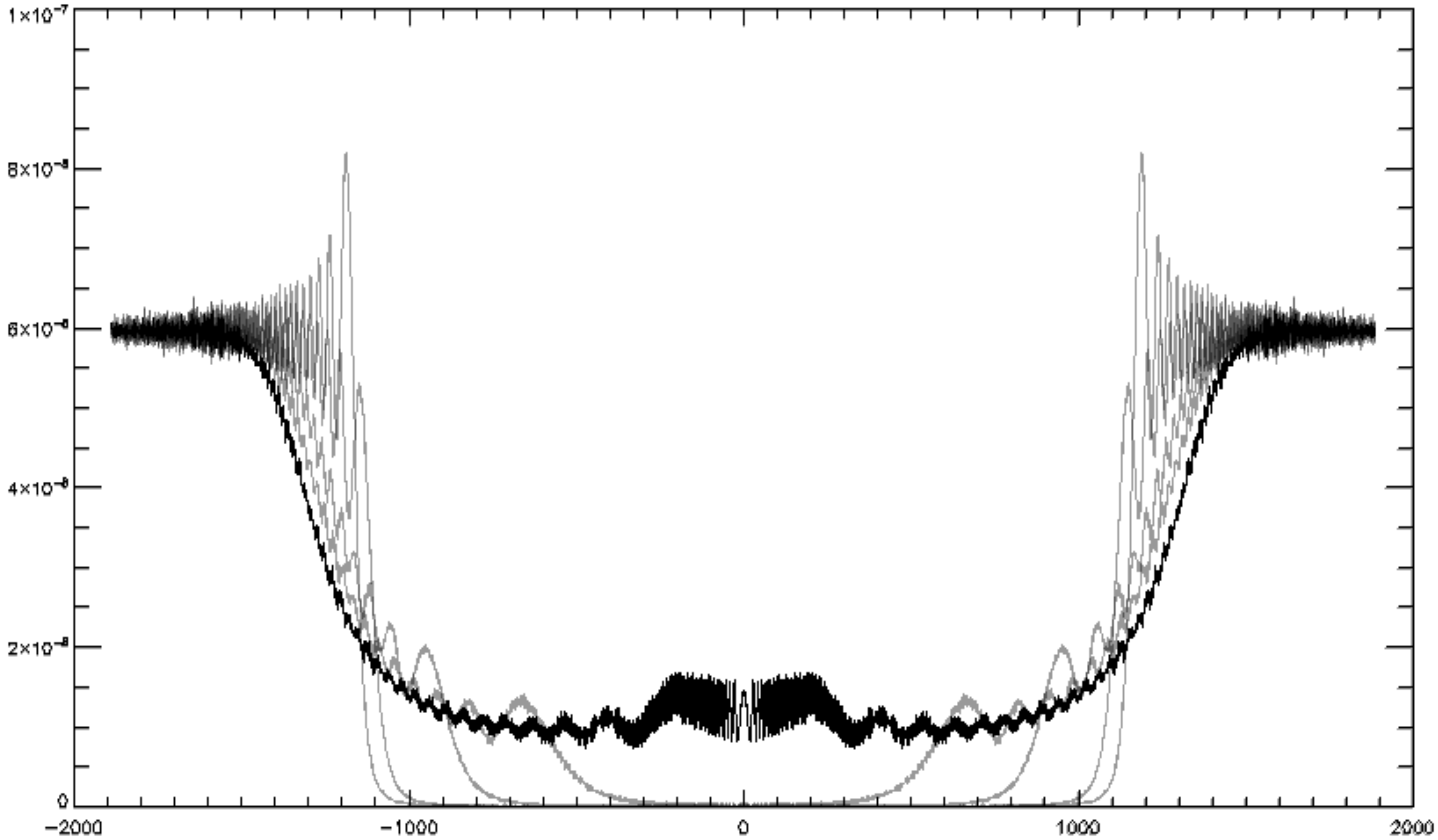
Transition from Diffraction to Refraction

1% of Pluto's Atmosphere



Transition from Diffraction to Refraction

2% of Pluto's Atmosphere



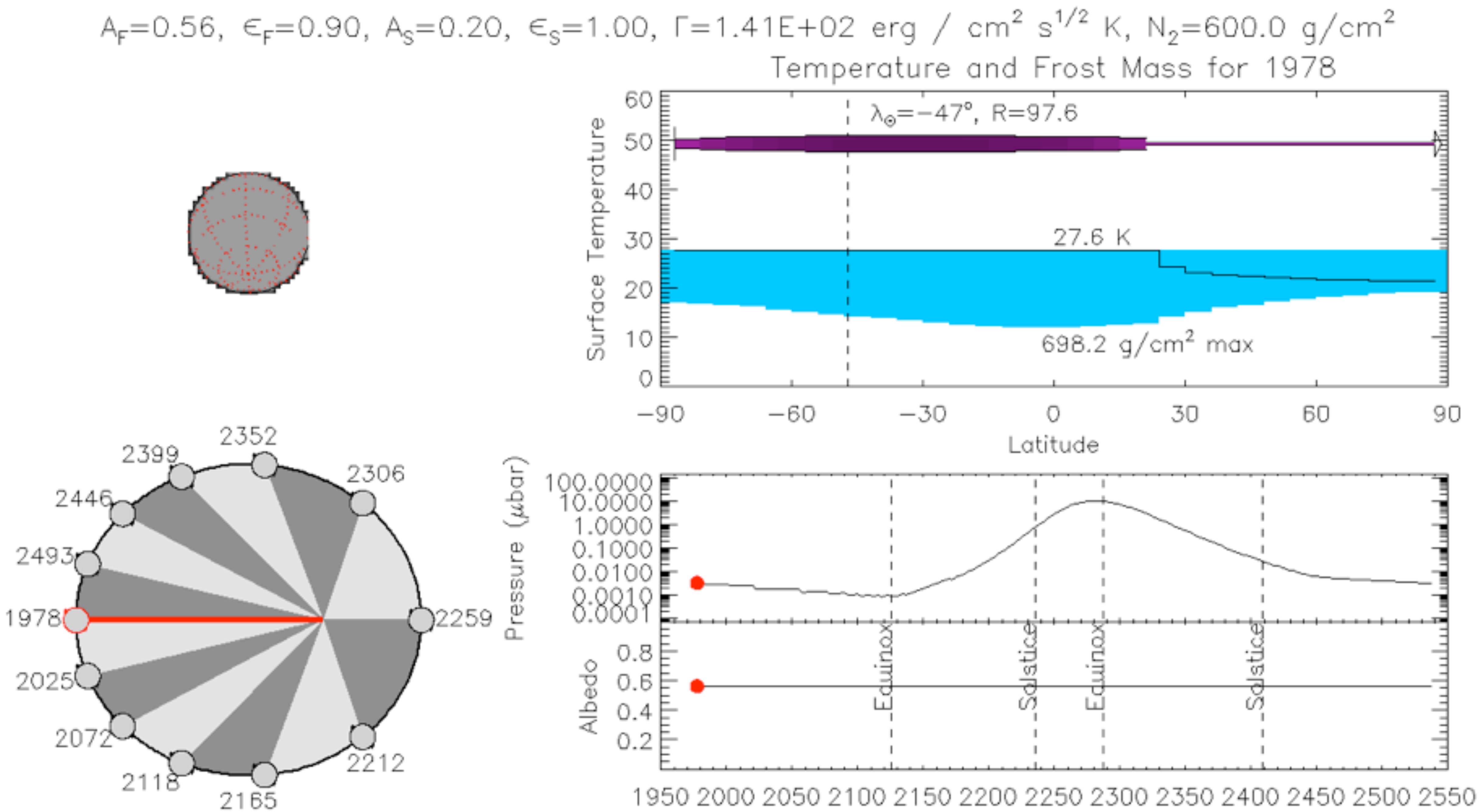
(Note: at real-world time resolutions, the very rapid oscillations in the lightcurve center are smoothed out.)

Relevance to Eris & other Large TNOs

- All of the large TNOs have large eccentricities and huge heliocentric distance variations.
- Eris and the other large TNOs are expected to transition between no atmosphere and thin atmospheres. Evidence for a seasonal atmosphere on Eris: its very high albedo.
- We now have a way of modeling and understanding the occultation lightcurves produced by very thin atmospheres.

A Year on Eris

- Prediction #1: Not all latitudes are covered in frost
- Prediction #2: Frost temperatures moderated considerably (26 - 37 K)
- Prediction #3: *Except* where winds cannot balance pressure gradients



Centrals Flashes and Titan

- If the observer lies close to center of the occultation path, it is possible to observe a *central flash*, a focusing of rays from various points on the limb.
- Central flashes are incredibly sensitive to the shape of an atmosphere.
- Case in point: the 28 Sgr occultation by Titan (3 JUL 1989).

Centrals Flashes and the 28 Sgr Occultation

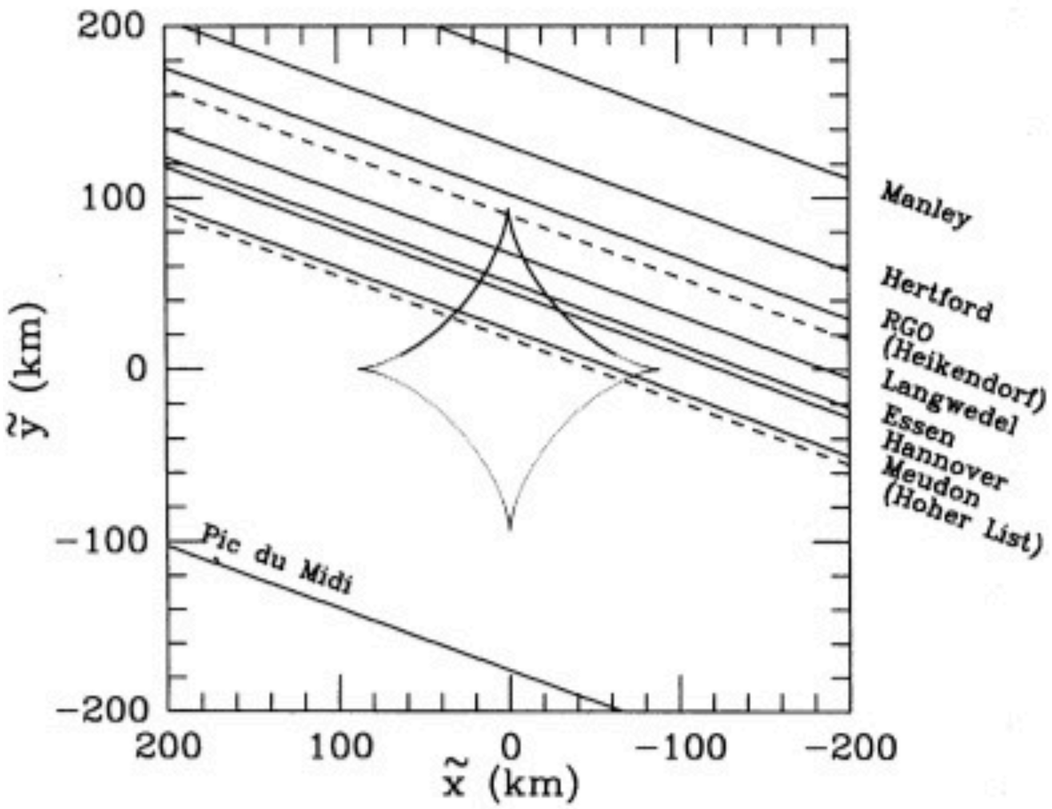


Fig. 30. The best-fit model for central caustics in the reference plane, assuming a simple oblate model for Titan's atmosphere. Portions of the caustics shown with light lines are missing because of large haze optical depth in Titan's northern hemisphere. *Dashed chords* show paths of stations with nonphotometric data. The coordinates $\tilde{x}$, $\tilde{y}$ are equivalent to x, y, but are rotated so that Titan's projected spin axis lies along the $\tilde{y}$ axis

The oblateness of level surfaces of an atmosphere in hydrostatic equilibrium rotating at angular rate ω is given by

$$e = \frac{3}{2} J_2 + \frac{1}{2} \frac{a\omega^2}{g}, \qquad (6)$$

where J_2 is Titan's dimensionless mass quadrupole moment, g is its atmospheric gravity (about 1 m/s^2), and $e = (a - b)/a$, where b is the true polar radius.

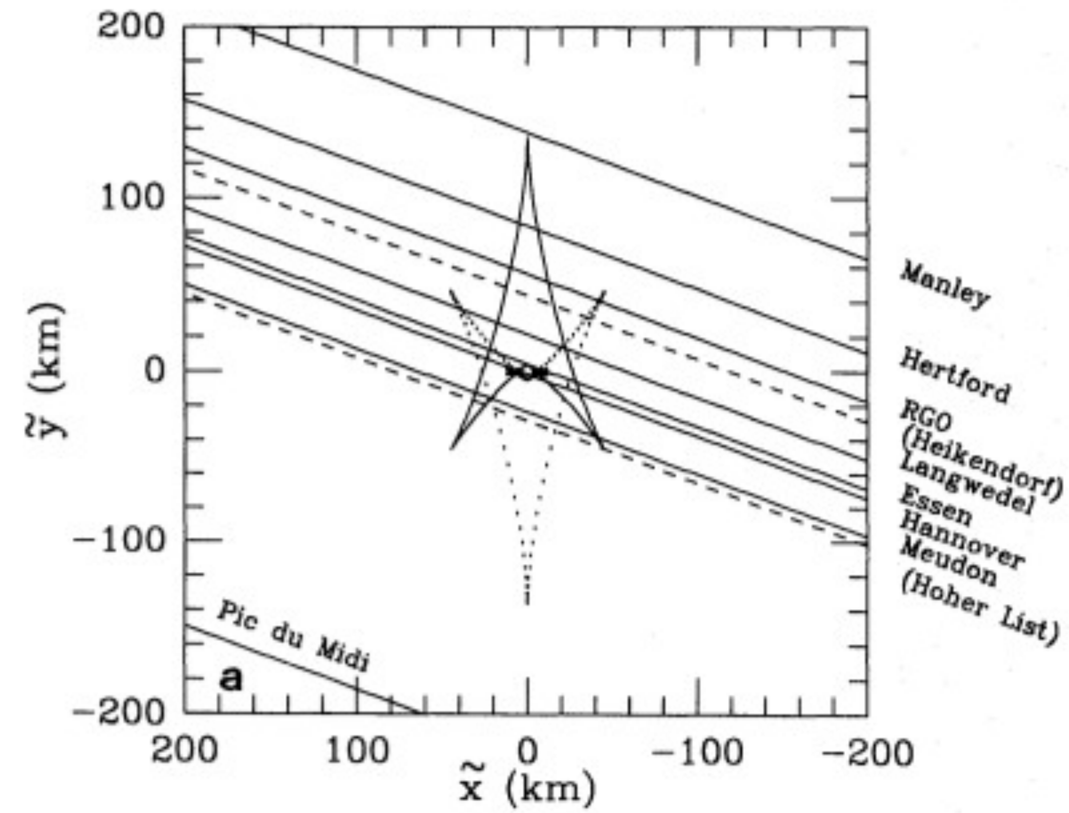
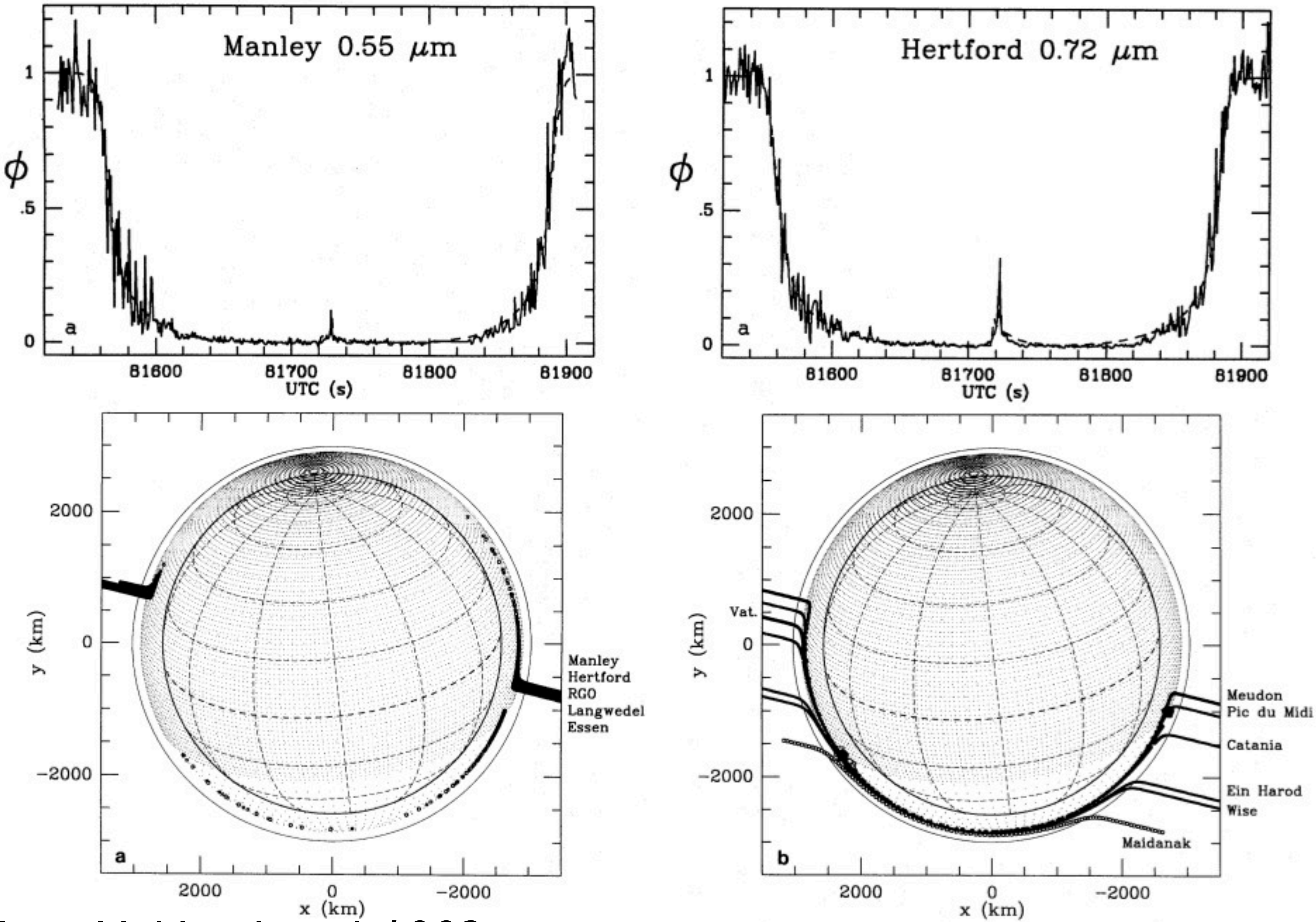


Fig. 33. (a) The best-fit model for central caustics in the reference plane, assuming a differentially-rotating model for Titan's atmosphere. Portions of the caustics shown with dotted lines are missing because of large haze optical depth in Titan's northern hemisphere. *Dashed chords* show paths of stations with nonphotometric data (Heikendorf, Hoher List). (b) Enlargement of the central region of (a). *Shaded circle* shows 28 Sgr's disk projected on the reference plane, with a radius = 9 km (Hubbard et al. 1992). Details of caustics at smaller scales are smeared out

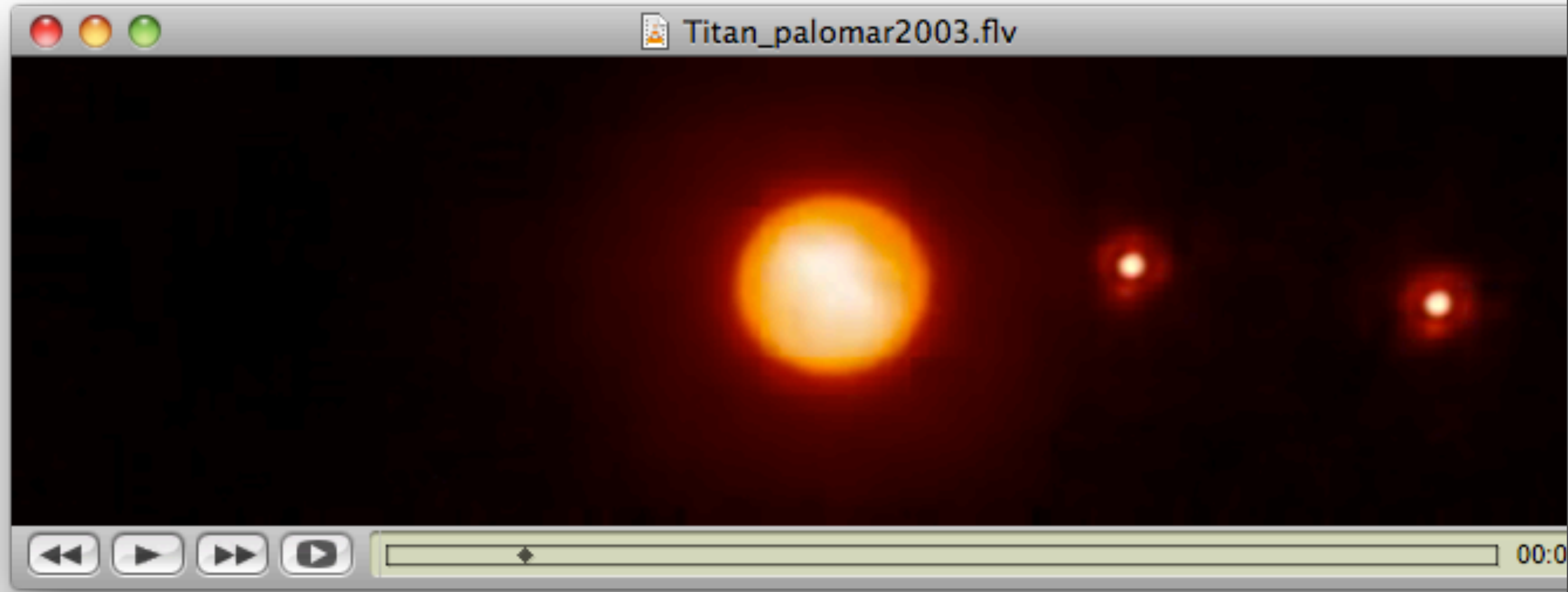
The central caustics require distortion by fast zonal winds.
From Hubbard et al. 1993

Centrals Flashes and the 28 Sgr Occultation

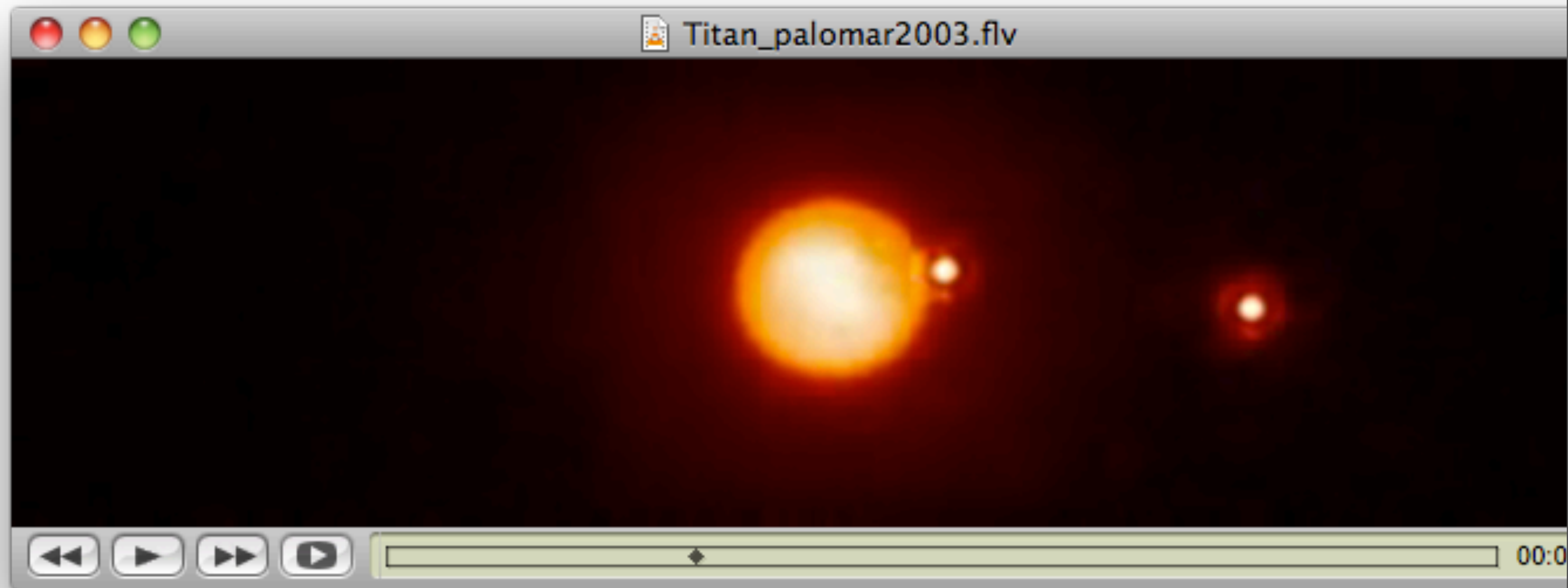


From Hubbard et al. 1993

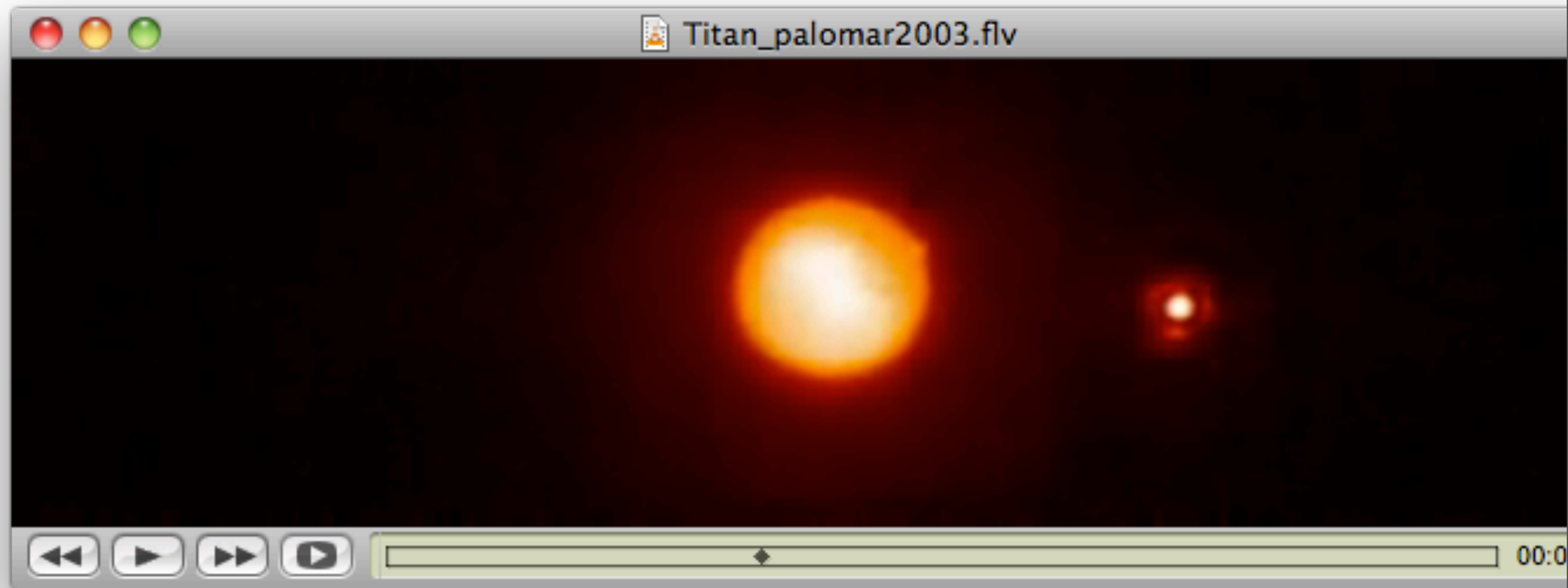
Centrals Flashes and the 2001 Titan Occ.



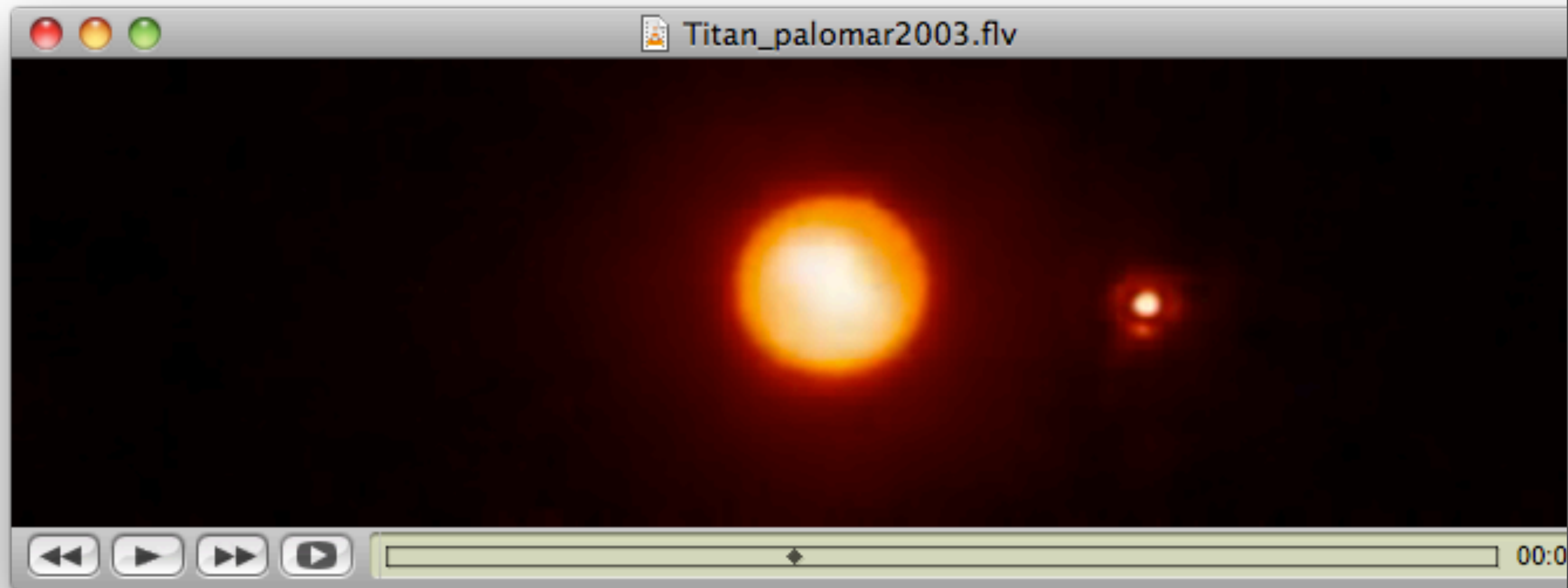
Centrals Flashes and the 2001 Titan Occ.



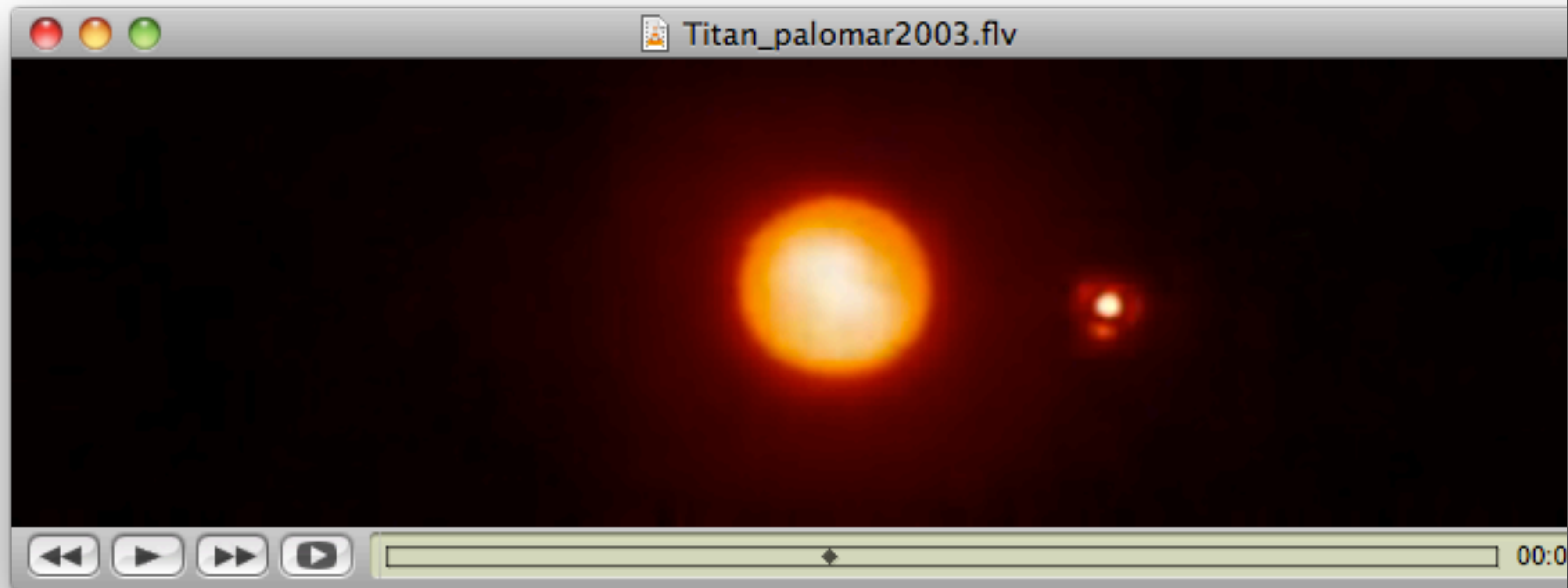
Centrals Flashes and the 2001 Titan Occ.



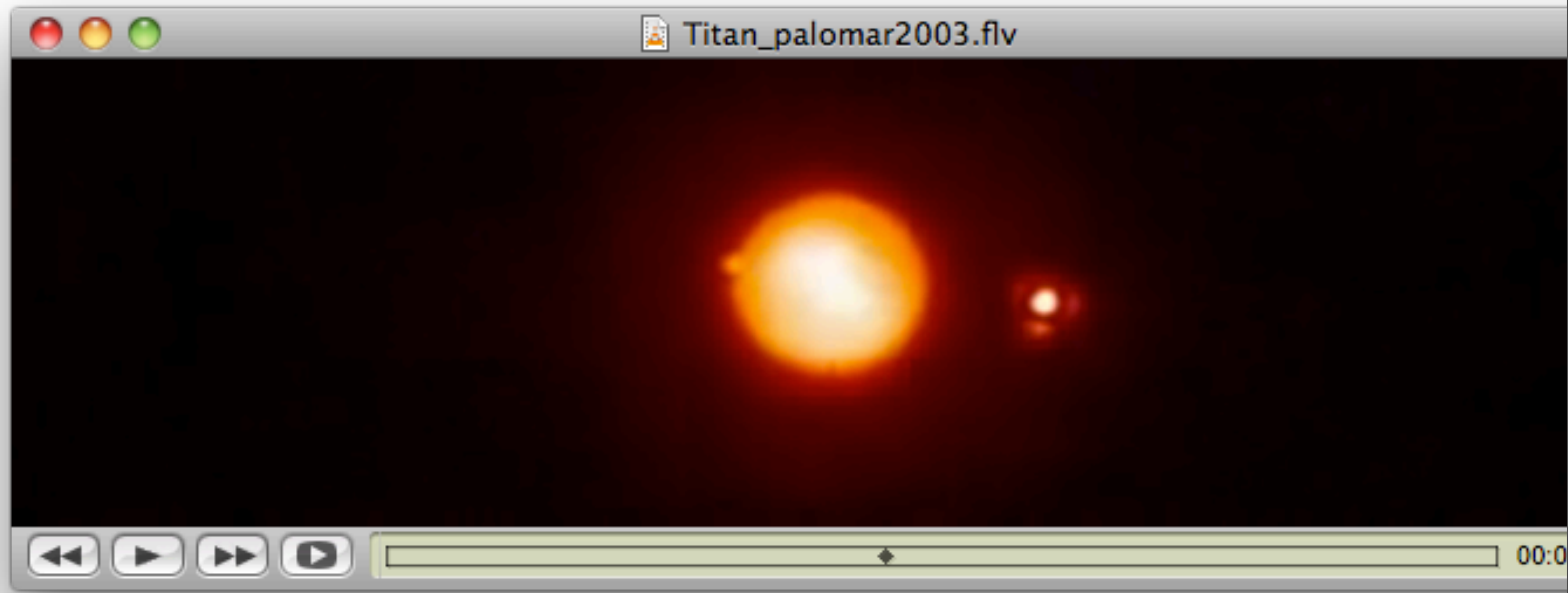
Centrals Flashes and the 2001 Titan Occ.



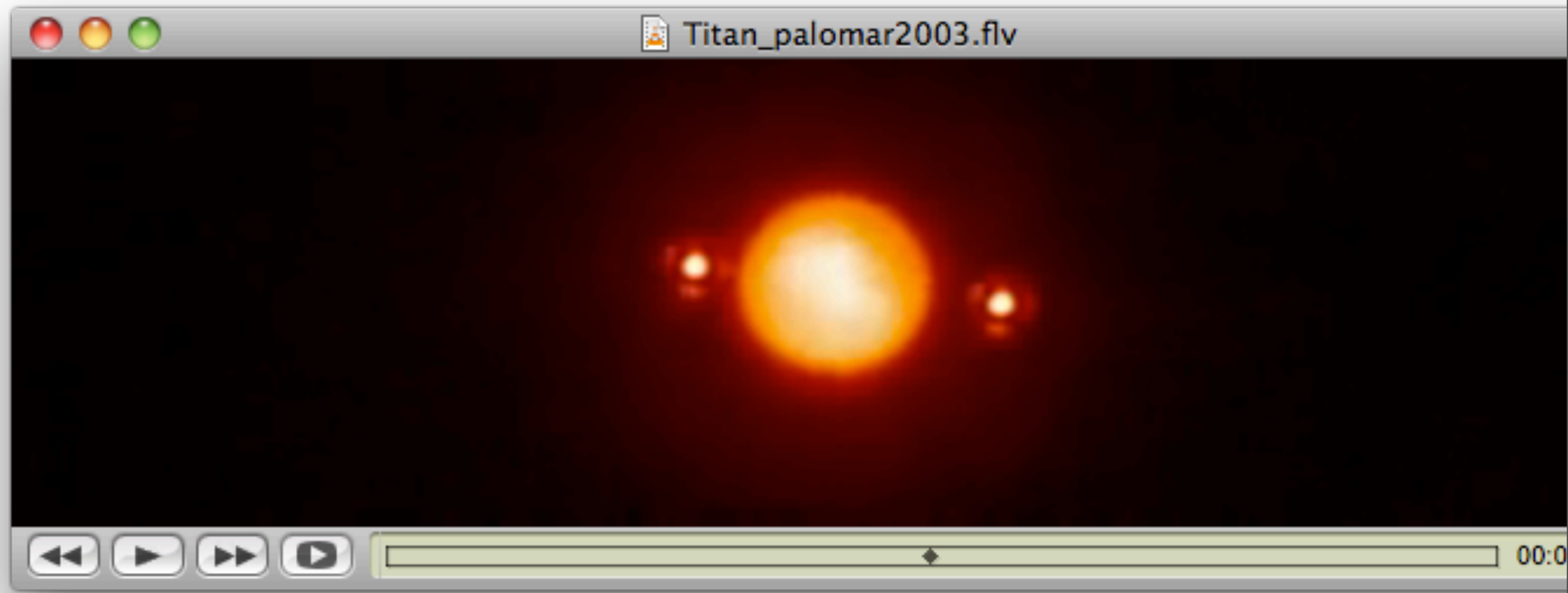
Centrals Flashes and the 2001 Titan Occ.



Centrals Flashes and the 2001 Titan Occ.



Centrals Flashes and the 2001 Titan Occ.



The 2003 Titan Occultation

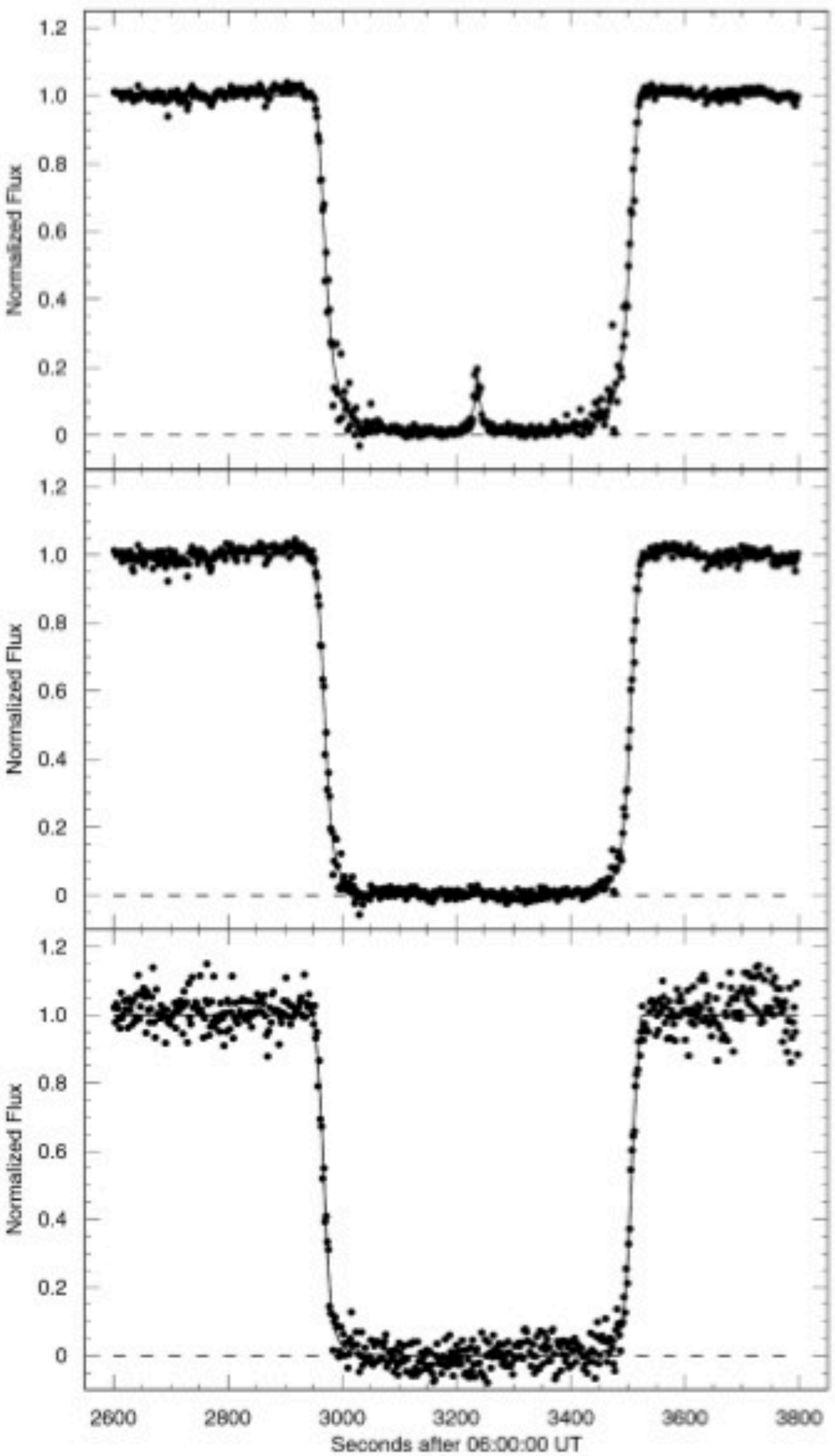


Fig. 3. Background-corrected light curves (points) for wavelengths i' (top), g' (middle), and u' (bottom). The dashed line indicates the zero flux level; the solid line (mostly obscured by the data points) is the model fit now with the background subtracted out. The data are averaged by 60 points (2 s), effectively averaging out the spikes. The correction to the i' and g' is very small.

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The 2003 November 14 occultation by Titan of TYC 1343-1865-1
II. Analysis of light curves

A. Zalucha[a,*], A. Fitzsimmons[b], J.L. Elliot[a,c,d], J. Thomas-Osip[e], H.B. Hammel[f], V.S. Dhillon[g], T.R. Marsh[h], F.W. Taylor[i], P.G.J. Irwin[i]

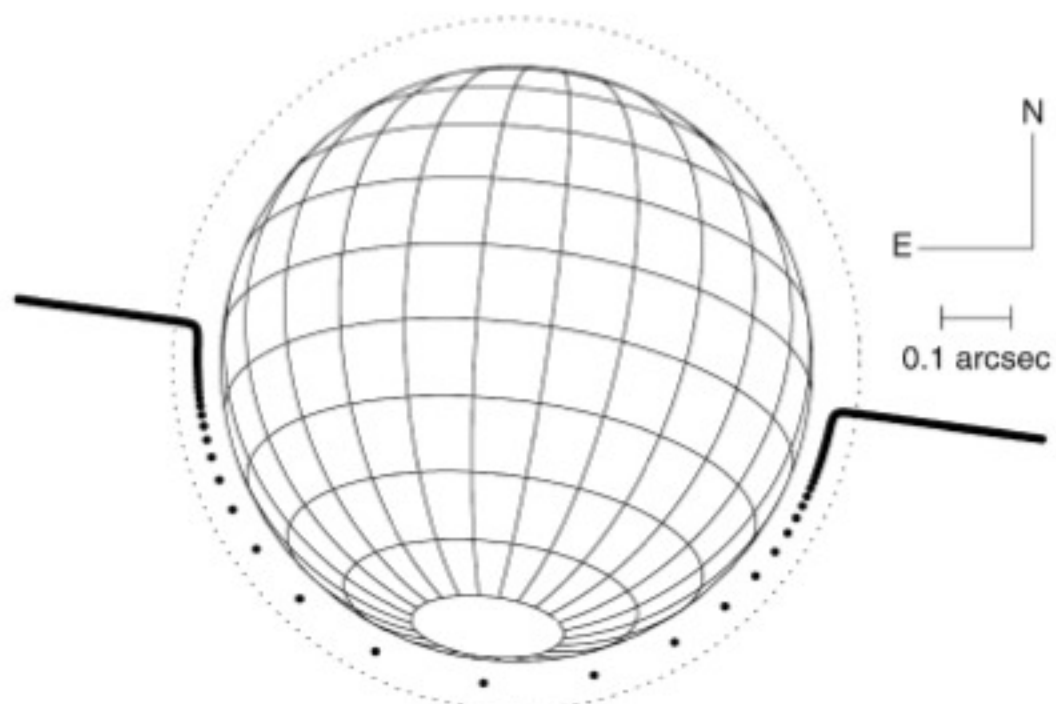


Fig. 1. Path of occultation star around Titan's limb as seen from Earth (heavy solid line and points). The star's path is in time increments of 1 s, showing that the star's image moves quickly around the southern part of the limb. The direc-

The 2003 Titan Occultation

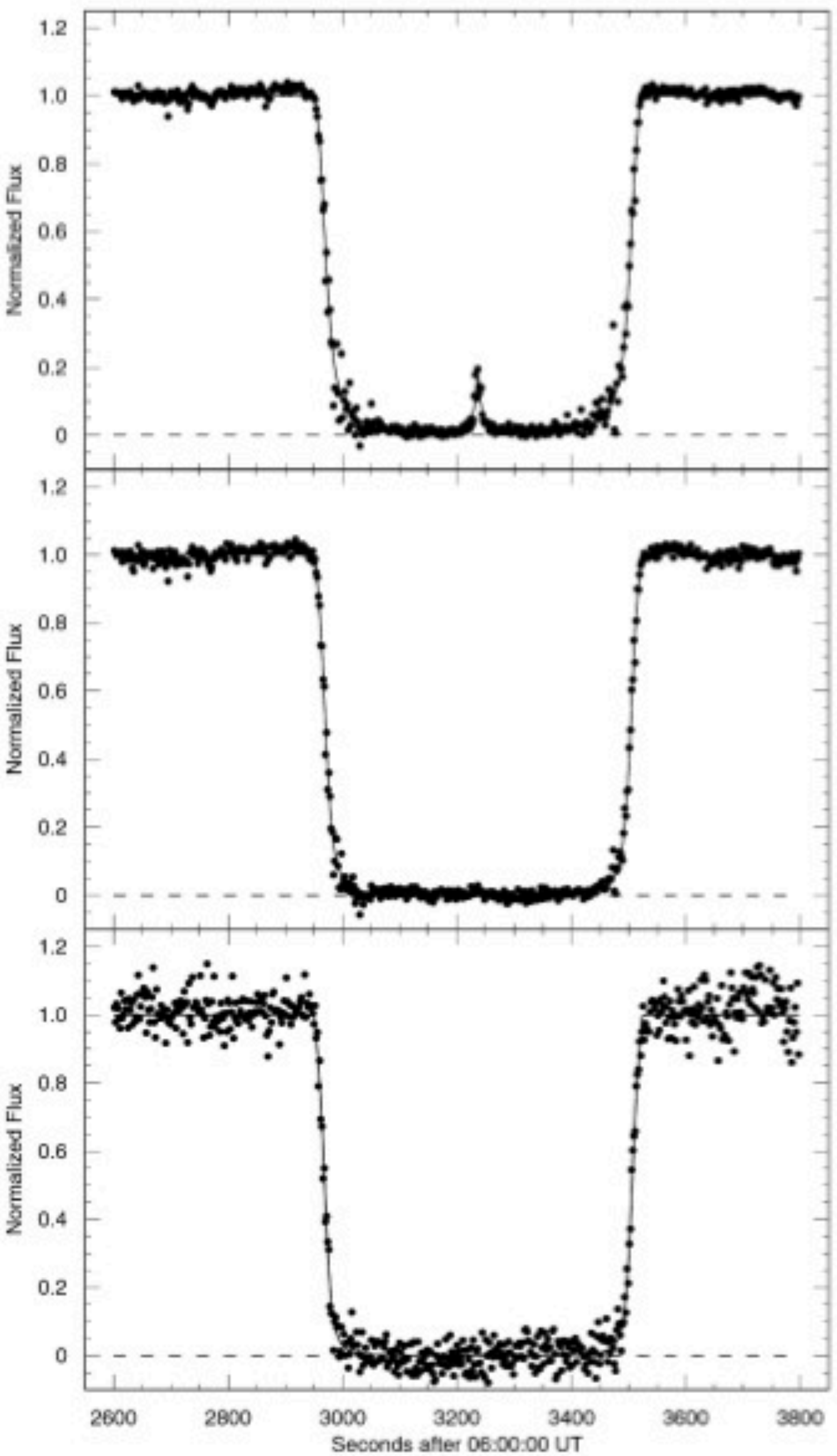


Fig. 3. Background-corrected light curves (points) for wavelengths i' (top), g' (middle), and u' (bottom). The dashed line indicates the zero flux level; the solid line (mostly obscured by the data points) is the model fit now with the background subtracted out. The data are averaged by 60 points (2 s), effectively averaging out the spikes. The correction to the i' and g' is very small.

Data was obtained with *ULTRACAM*, which is well-suited for occultations:

- obtains 3 colors simultaneously (*i'*, *g'*, *u'*)
- with a cadence of 30 Hz (in this case).

A Central Flash is observed, but only in the *i'* filter. Reason: the effective aerosol optical depth is less at the longer wavelength.

Zalucha et al. (2007) fit a model atm. with this thermal profile and an exponential haze profile.

$$T(r) = T_H \left(\frac{r}{r_H}\right)^b, \tag{1}$$

where T is temperature, T_H is the half-light temperature, r is the radius from the body's center, r_H is the half-light radius,

The 2003 Titan Occultation

Table 1
Results from light curve model fit

	Filter		
	i'	g'	u'
Fixed parameters			
Number of points fit (after averaging)	598	598	598
Shadow velocity,[a] V (km s^{-1})	11.25	11.25	11.25
Integration time, Δt (s)	2	2	2
Full-scale level, s_f	1	1	1
Thermal gradient parameter, b	−1.5	−1.5	−1.5
Fitted parameters			
Background fraction, s_{bf} (10^{-2})	-1.2 ± 0.3	0.5 ± 0.2	16.6 ± 0.4
Background slope, s' (10^{-5} s^{-1})	1.8 ± 0.3	1.5 ± 0.2	13.4 ± 0.5
Half-light radius,[b] r_H (km)	2992 ± 13	2967 ± 10	2971 ± 23
Half-light equivalent isothermal lambda, λ_{Hi}	51 ± 3	56 ± 2	62 ± 11
Radius of extinction onset, r_1 (km)	3173 ± 22	3194 ± 9	3214 ± 20
Radius of optical depth unity, r_2 (km)	2868 ± 5	2923 ± 4	2956 ± 11
Haze scale height, $H_{\tau 1}$ (km)	90 ± 15	97 ± 8	97 ± 20
Time of closest approach, t_{mid} (seconds after 2003 11 14 06:00:00 UT)	3236.1 ± 0.2	3236.3 ± 0.1	3236.7 ± 0.3
Distance of closest approach,[c] y_{min} (km)	39 ± 8	39	39
Derived parameters			
Temperature at half-light[d] (K)	185 ± 11	172 ± 6	156 ± 27
Pressure scale height at half-light[e] (km)	55 ± 3	50 ± 2	45 ± 8
Half-light altitude (km)	417 ± 13	392 ± 10	396 ± 23
Altitude of extinction onset (km)	598 ± 22	619 ± 9	639 ± 20
Altitude of optical depth unity (km)	293 ± 5	348 ± 4	381 ± 11

[a] Velocity near the occultation mid time. The respective velocities at the beginning and end of the occultation were 11.26 and 11.23 km s^{-1}.
[b] The surface radius of Titan is 2575 km.
[c] Fit for i' only; n.b. the central-flash analysis yields a closest approach distance of 19 km.
[d] Given by $\mu m_{amu} G M_p / k(\lambda_{Hi} - 5b/2) r_H$; see Table 2 for values of μ and M_p.
[e] Given by $r_H / (\lambda_{Hi} - 5b/2)$.

The 2003 Titan Occultation

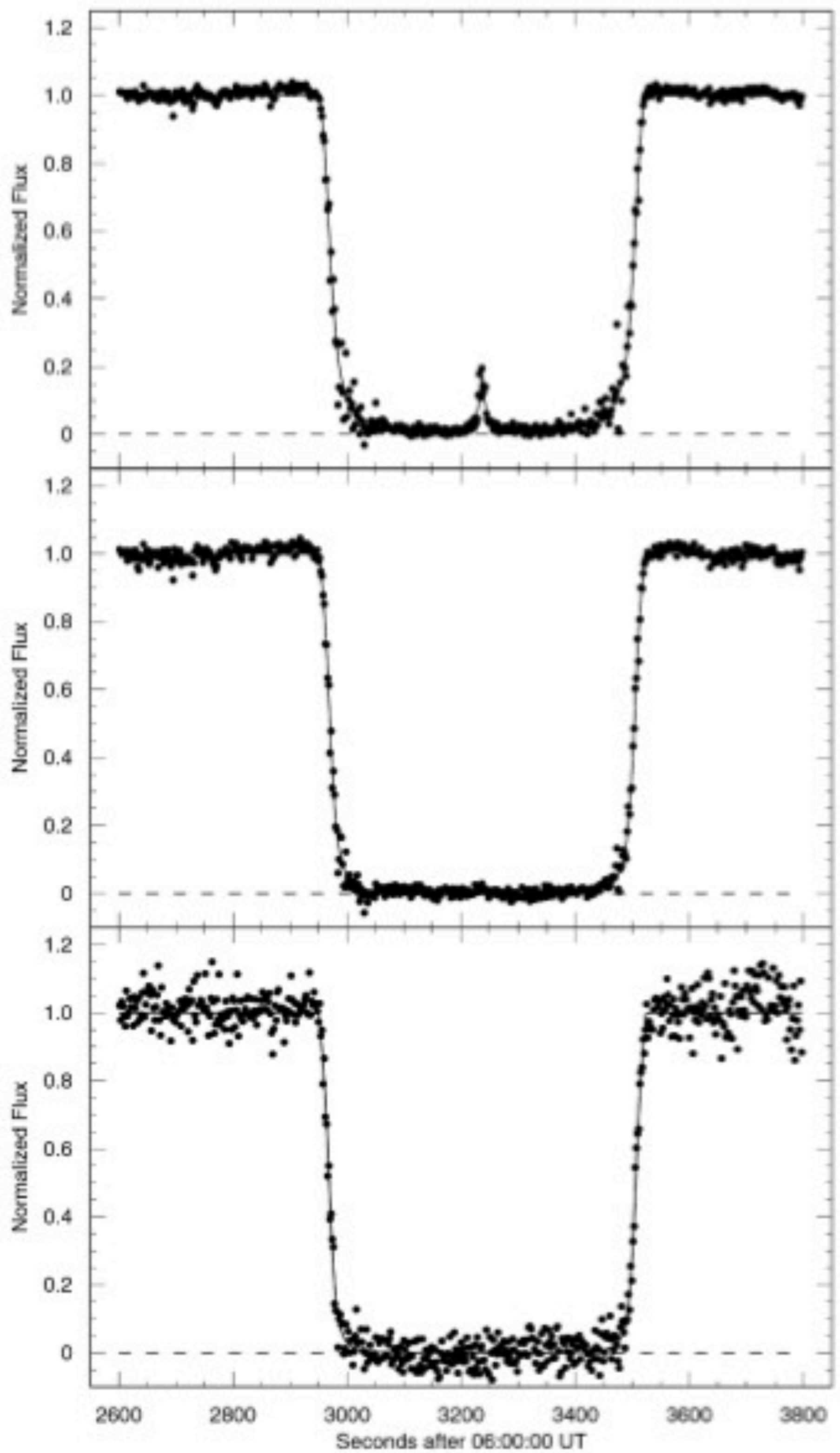
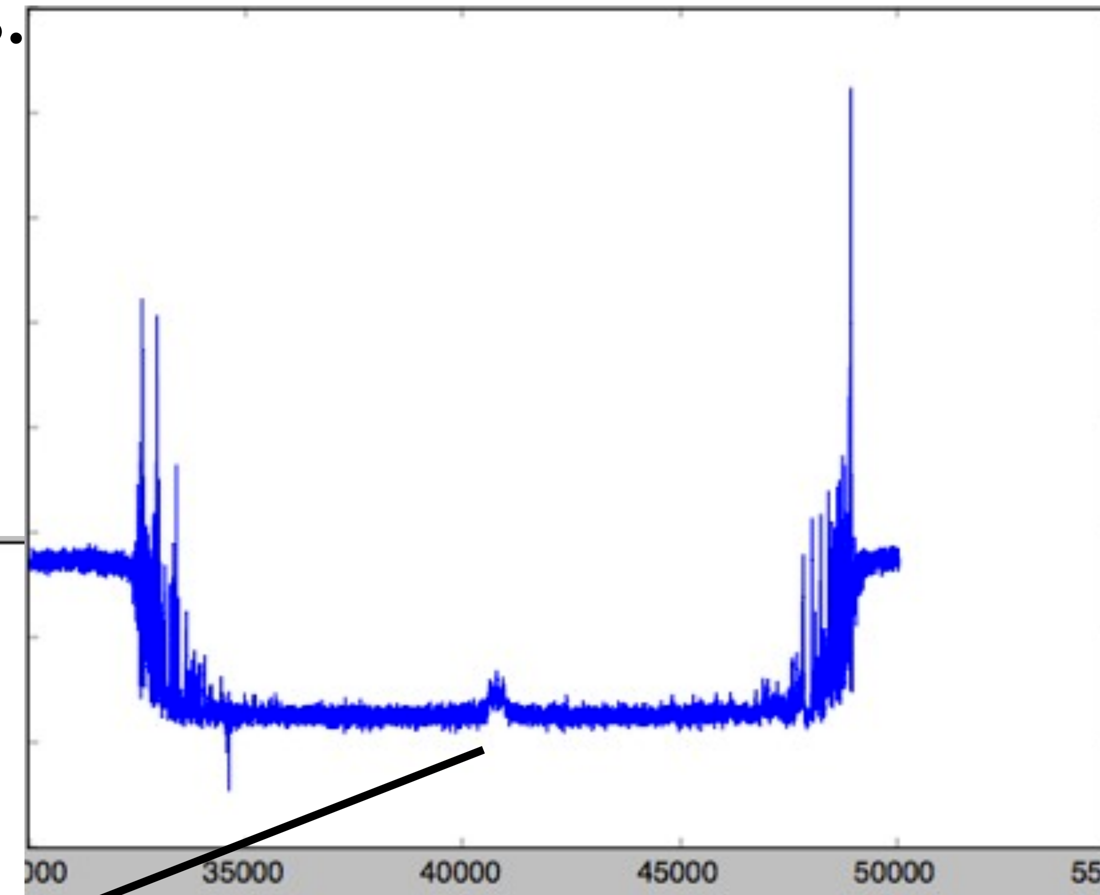
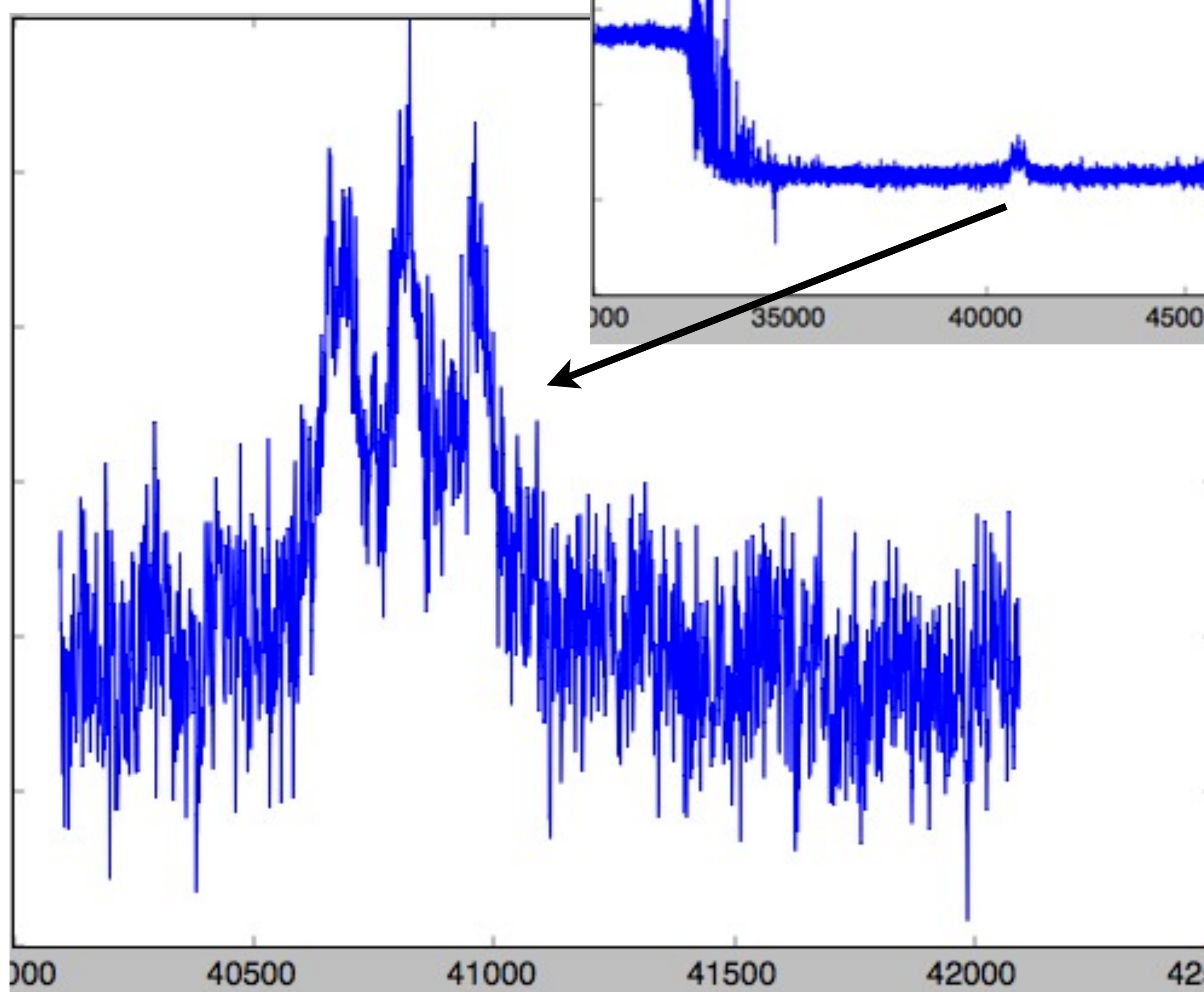


Fig. 3. Background-corrected light curves (points) for wavelengths i' (top), g' (middle), and u' (bottom). The dashed line indicates the zero flux level; the solid line (mostly obscured by the data points) is the model fit now with the background subtracted out. The data are averaged by 60 points (2 s), effectively averaging out the spikes. The correction to the i' and g' is very small.

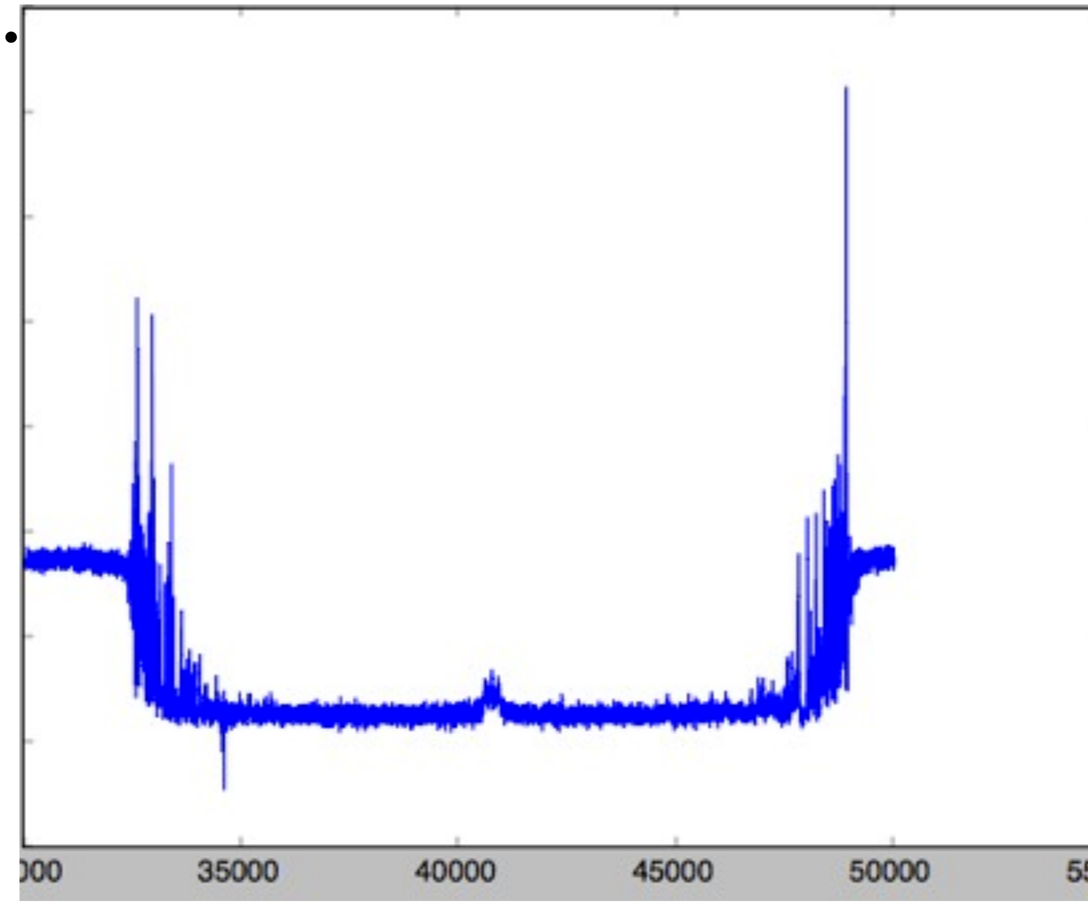
Taking a closer look at the central flash and scintillations.





The 2003 Titan Occultation

Taking a closer look at the central flash and scintillations.



12 A. Fitzsimmons et al.: High-cadence multi-colour occultation lightcurves of Titan

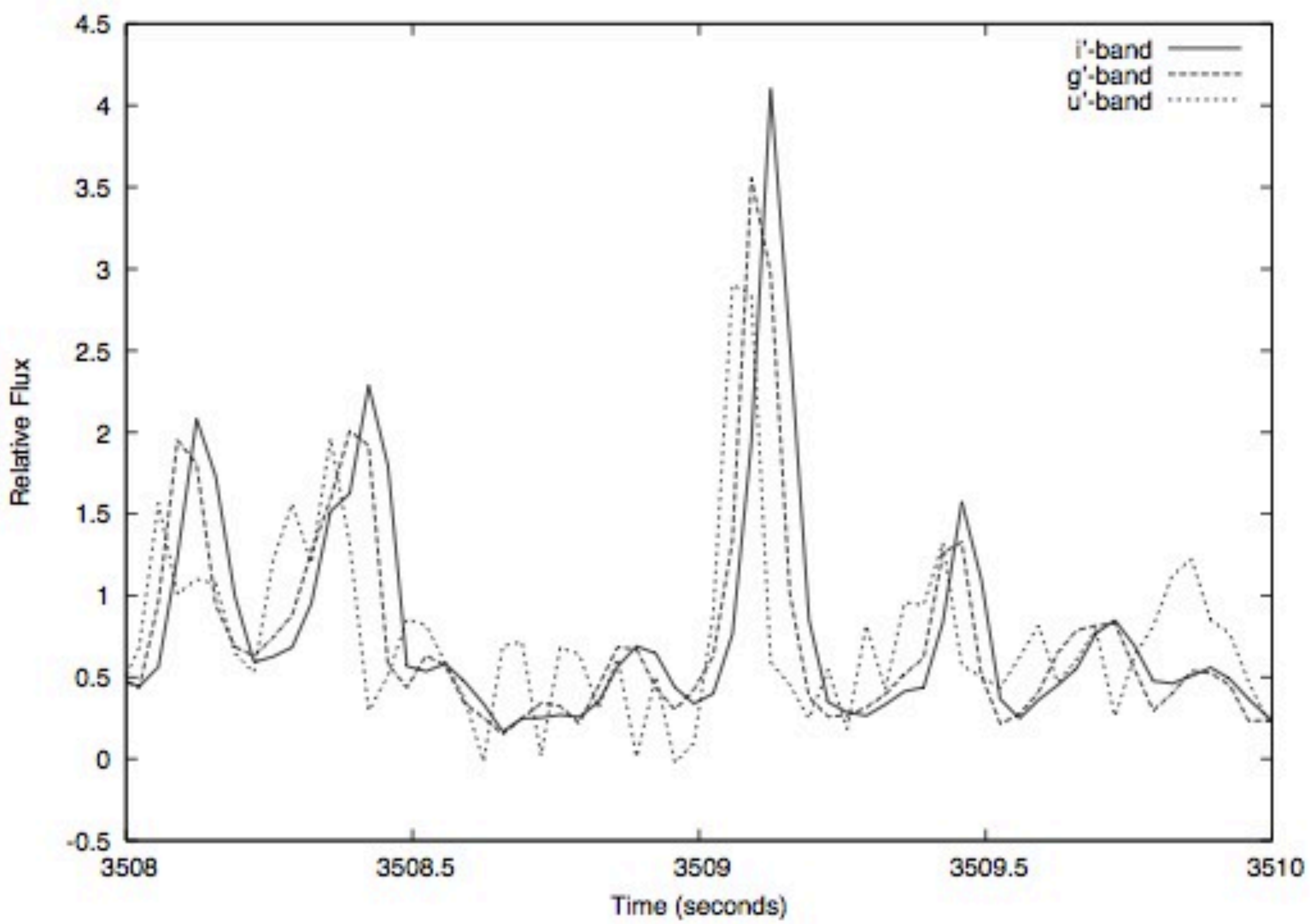


Fig. 7. Detail of the largest amplitude scintilation event seen in our data, during emersion at t = 3509.1 sec in the i' filter. The refractive delay in the detection of these events can be clearly seen from comparing the individual lightcurves.

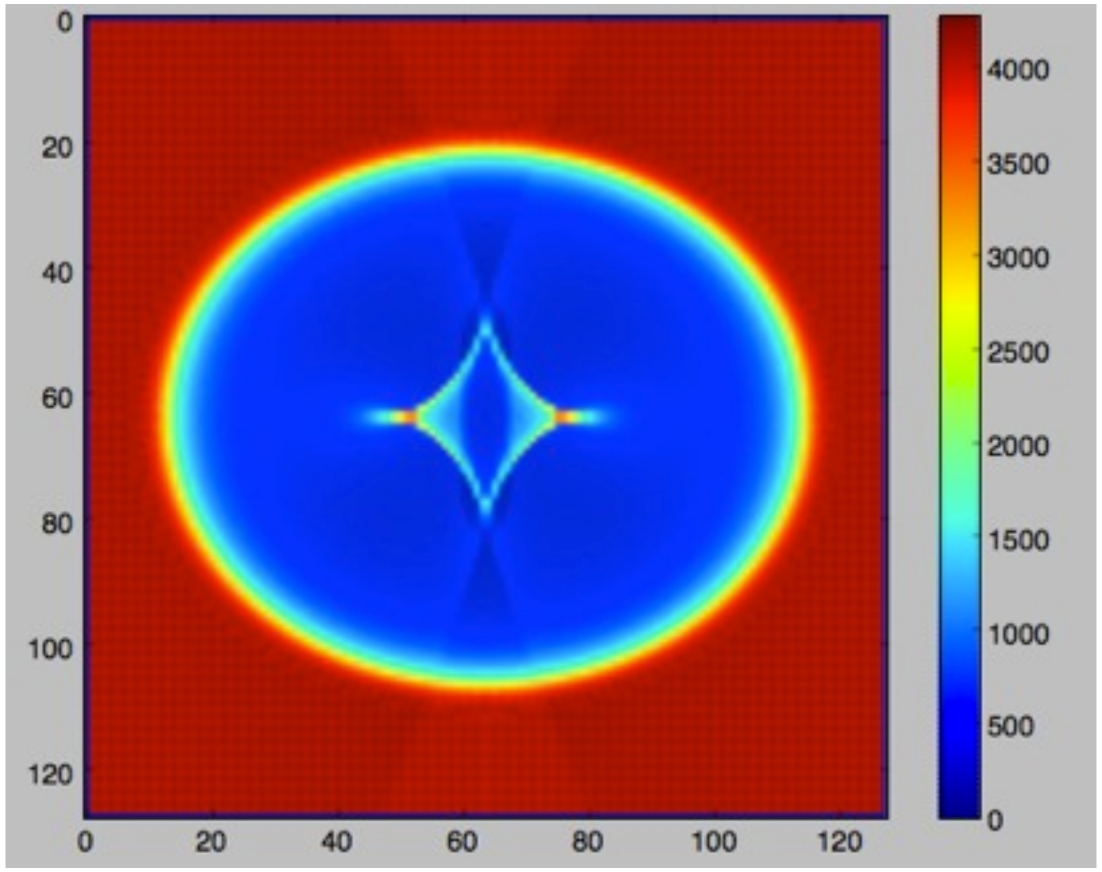
Remarkably, the scintillations are apparent in all three filters, but with an observable offset. Cause: the macroscopic effect of refractivity vs. wavelength.

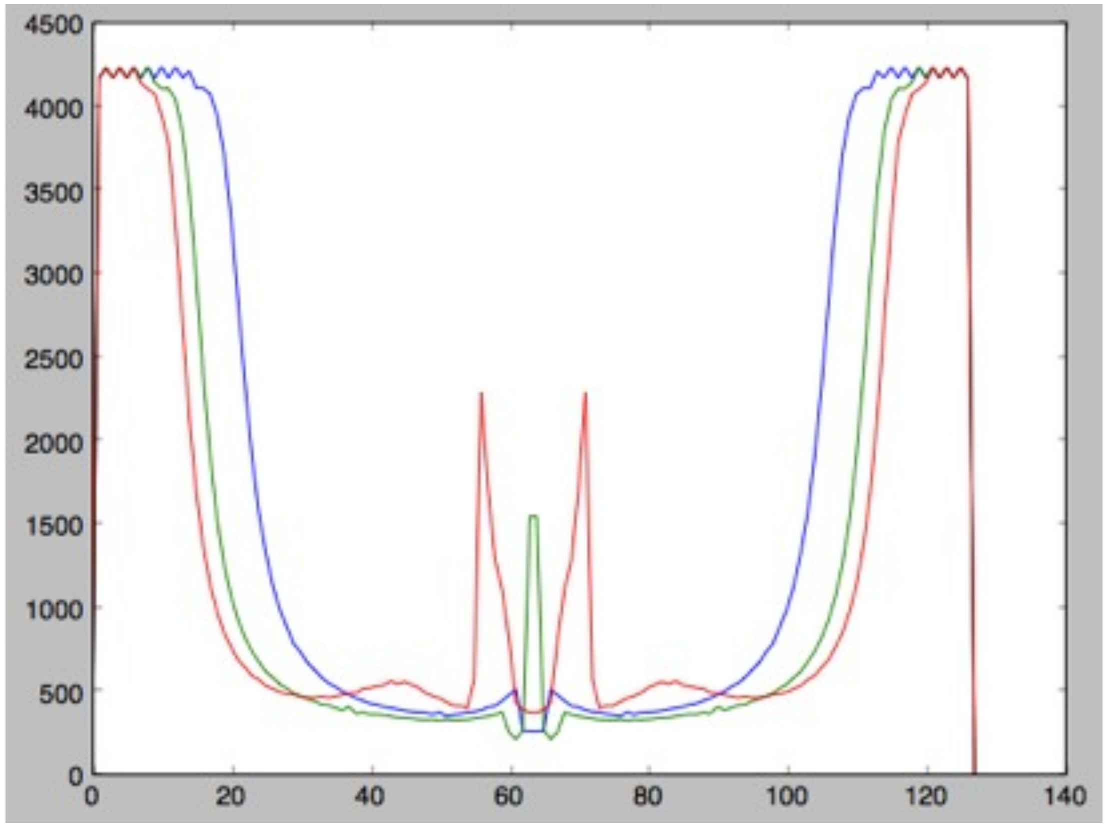
The 2003 Titan Occultation

Generating Occultation Lightcurves in four easy steps:

- Assume a THIN SCREEN,
- Calculate the phases and opacities,
- Get the *Bending Angle* from the gradient of the phases.
- Shoot a lot of rays into the screen. Collect them onto a virtual hit plate.

Oblate "Titans" generate caustics, as expected.



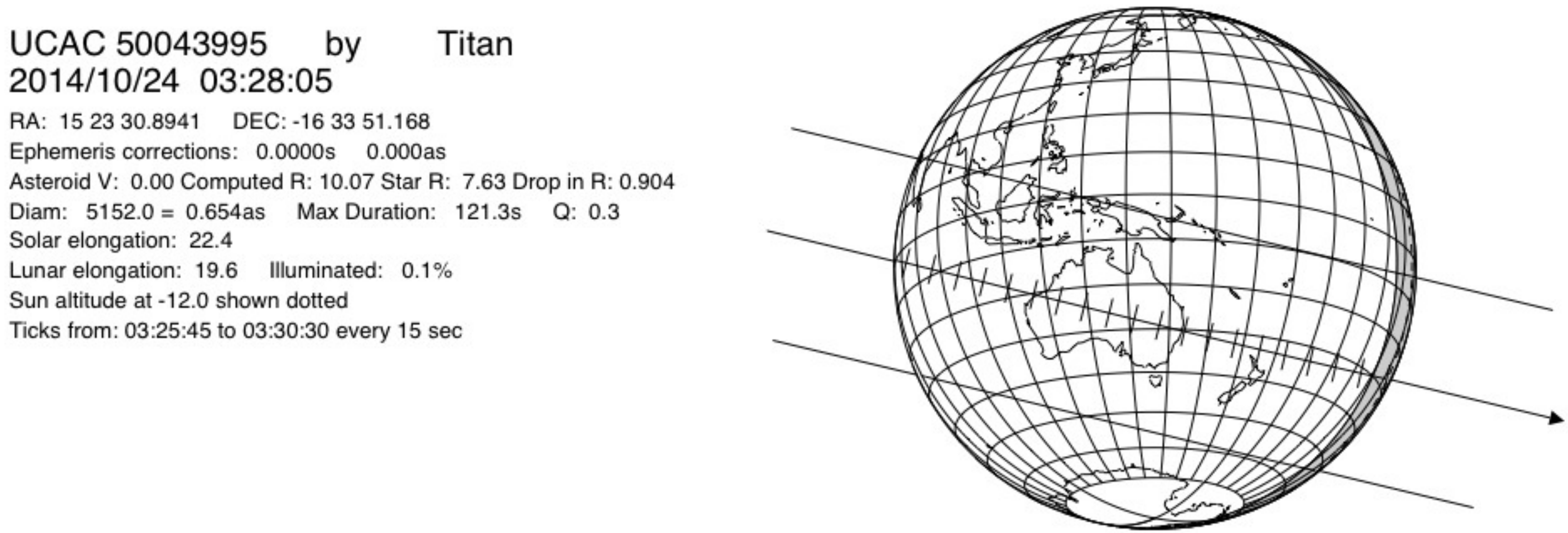


The 2003 Titan Occultation

Why observe Titan as it occults a star? After all, Cassini gets radio occultations during Titan fly-bys.

- Occultation lightcurves complement the Cassini/ISS images of Titan: both provide about 1 km vertical resolution, but occultations add temperature, density and pressure profiles from about 200–500 km. The combination will help examine whether haze layers form because of vertical temperature structure or whether the haze layers are the primary causes of temperature structure.
- Cassini is too close to see ray crossing patterns. Terrestrial observers are better situated to measure central flash caustics. Goal: measure Titan's figure in detail and constrain zonal winds.

Future Work: A 2014 Titan Occultation



A very bright occultation in October 2014, but occurs during daylight.

Plenty of signal if we take steps to reduce the sky background:

- Observe in IR (e.g., 1.5 μm)
- Observe from a balloon (100x reduction in sky background)