

Photometry of Outer-belt Objects

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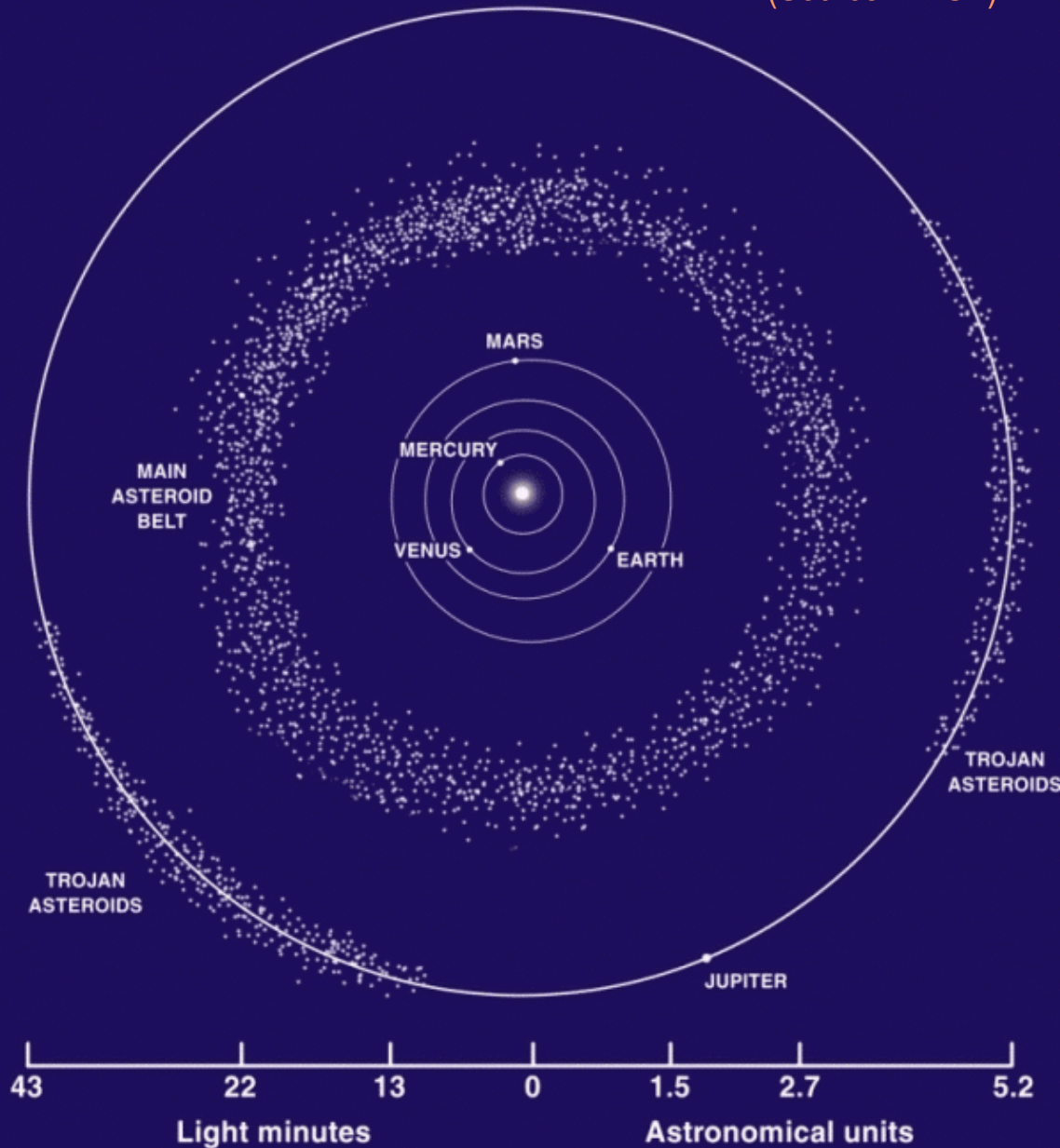
Outer-belt Objects: Minor Planets

Eros (Source: NEAR)



- 1 Ceres - Discovered 1801 Jan 1 by Guiseppe Piazzi – dubbed “asteroid” by William Herschel 1802.
- Only remaining “planetesimals” that date back to the formation of the solar system.
- Substantial collisional evolution – no orbit, thermal or geological evolution (Binzel, R. P. 1989, Asteroids II) – blueprint for conditions in early solar system.
- Occupy transition region between terrestrial planets and Jovian (gas giants) planets (2-3.5AU)

(Source: NASA)



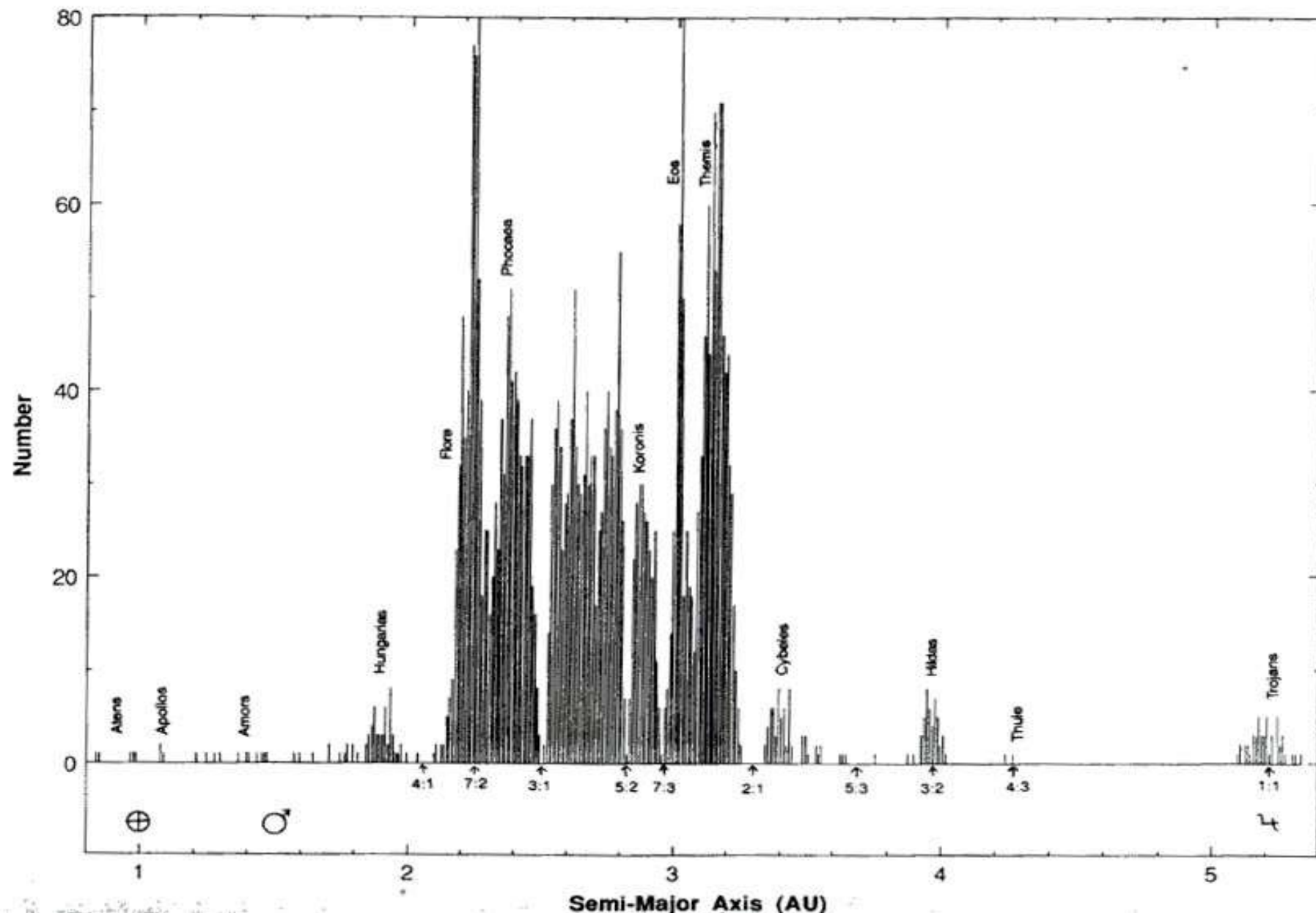
Large gap between orbits of Mars and Jupiter – led to search for planetary body in the region – Titus-Bode rule.

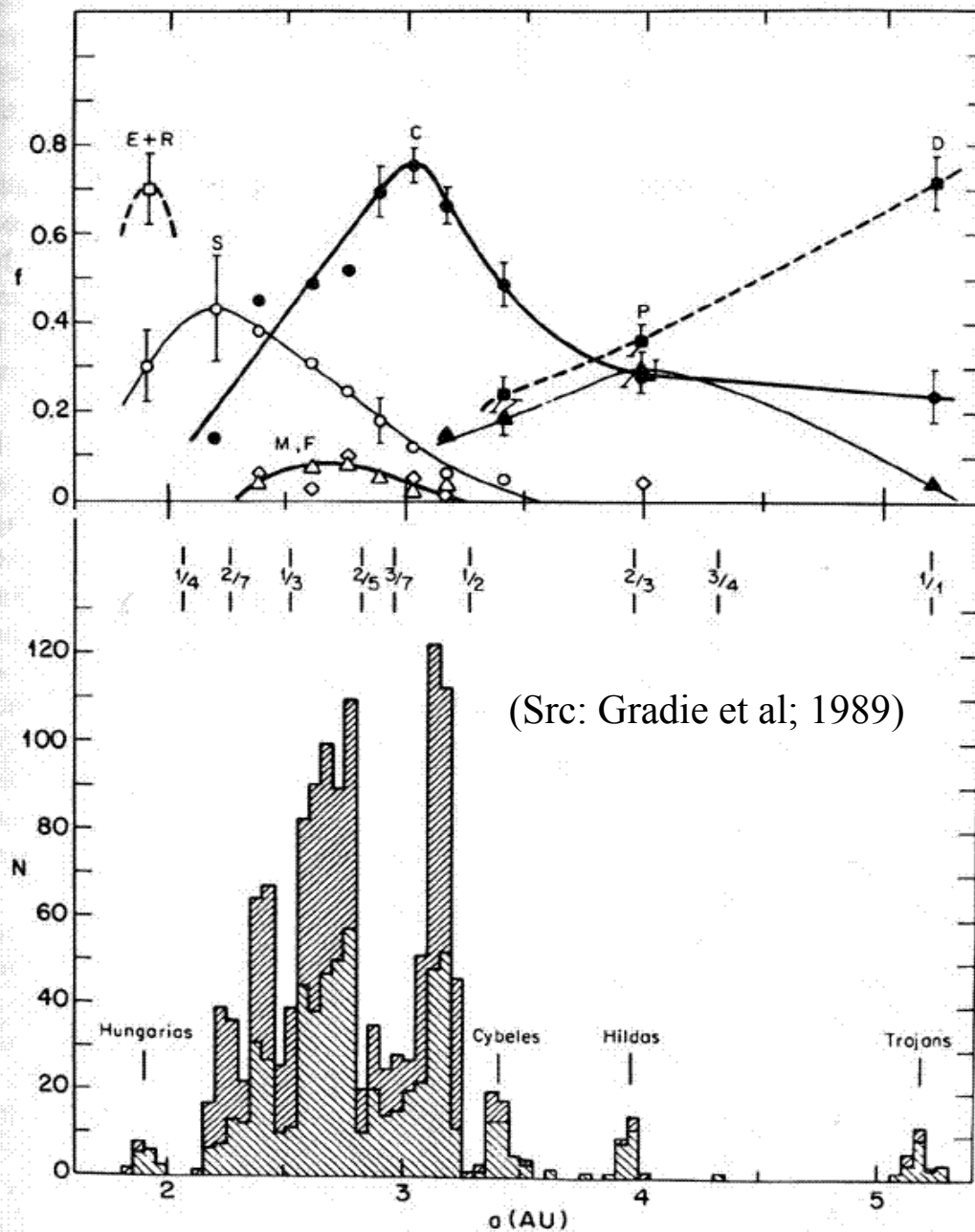
Theories (Wetherill, G. W. 1989, Asteroids II)

- Not enough density to cause planet formation. **Why?** Meteorite data constrain asteroid formation time to < 100 Myr.
- Never much material there to begin with – cannot be ruled out as we don't fully understand solar nebula and accretion disk. Unlikely as lowest surface density still too high by 100x.
- If there was enough material $<$
- Collisional fragmentation followed by loss of small fragments through different processes. Collision relative velocity must be sufficient to overcome mechanical strength ~ 2 km/s for largest asteroids. Present relative velocities ~ 5 km/s.
- Gravitational perturbations by Jovians cause eccentric short-lived orbits.

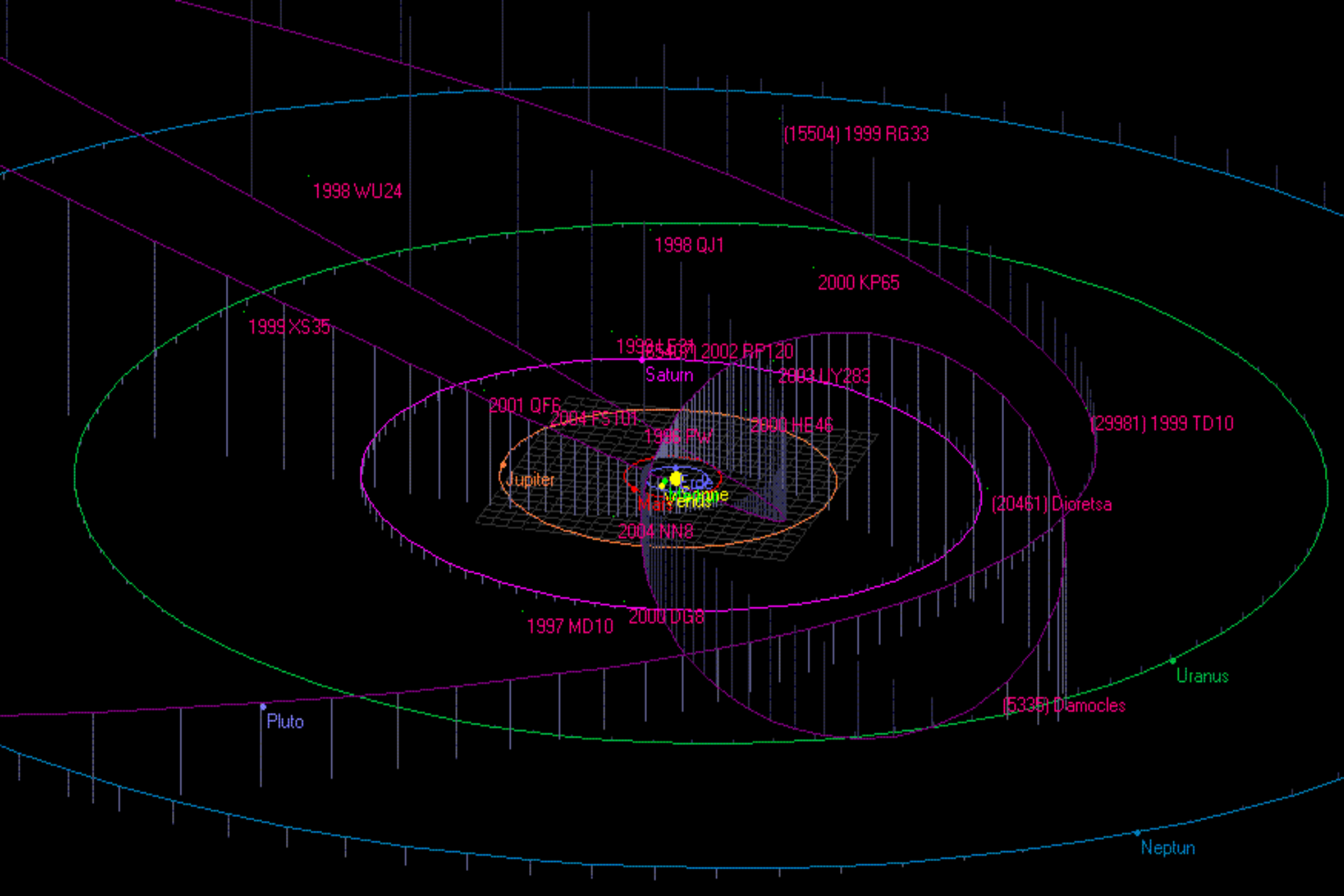
Distribution of Asteroids and Families vs. Semi-Major axis – Orbital Resonances

(Src:
Binzel
1989)



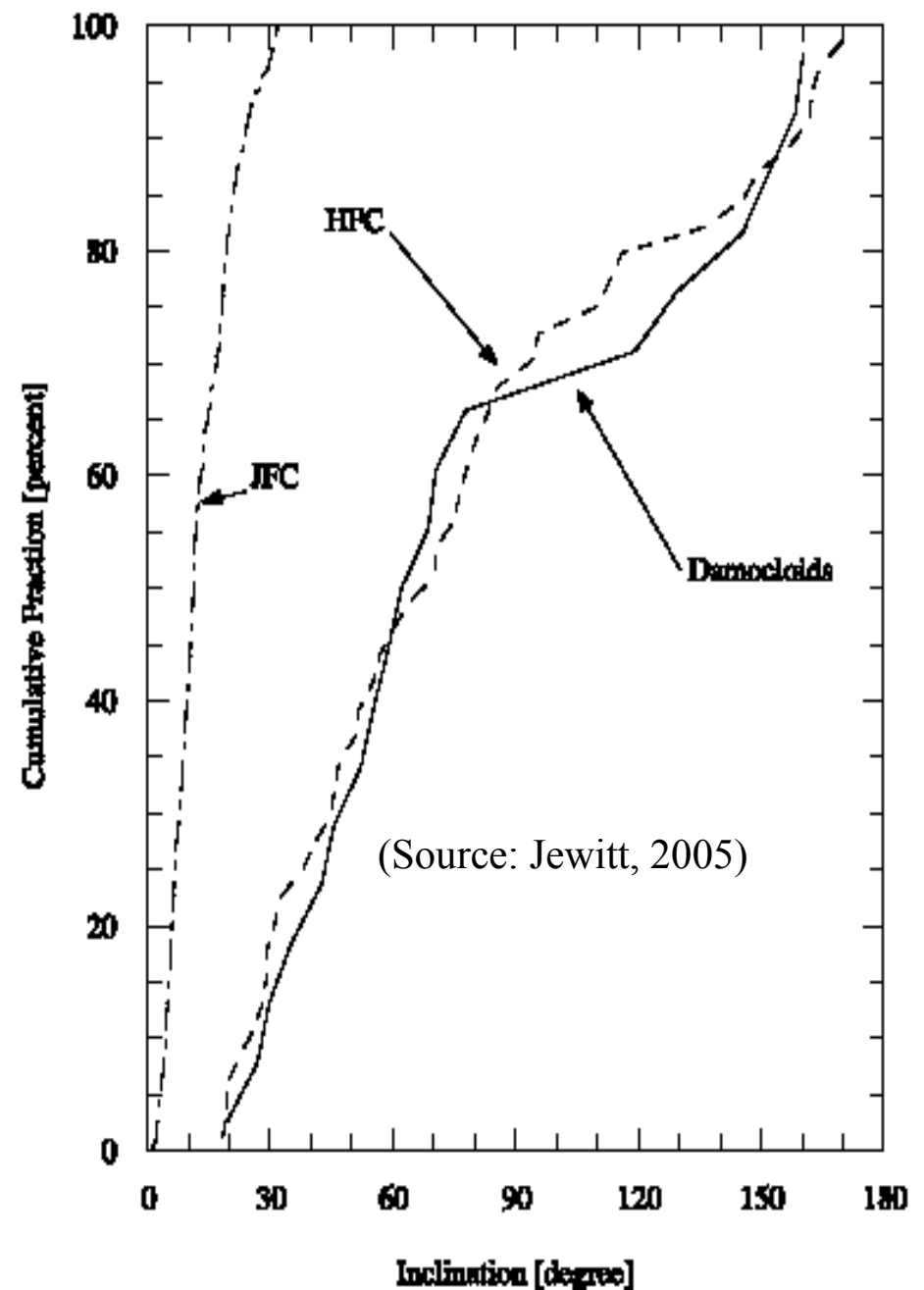


- S-type: Inner main belt, moderate albedo, red-spectra shortward of 700nm – small or no infrared absorption features
- M-type: Features from 300-1100nm (identical to E and P) but with higher albedo - thought to be metallic (Ni-Fe) compositions but with varying metal contents
- C-type: Features above 400nm – similar in surface composition to carbonaceous chondrites. UV absorption feature – relative strength correlates with presence of water of hydration (B, F, G subclasses)
- D-type: Rare in main-belt – very red spectra above 550nm. Some spectra flatten above 950nm.



Damocloids

- Named for 5335 Damocles, the first object found – highly inclined orbit almost perpendicular to the plane of the ecliptic.
- Highly inclined and eccentric orbits – normally characteristic comets like Halley Family Comets (HFCs) – perhaps nuclei of burned out comets (Asher et al; 1994)
- Orbital elements can be shown to be dissimilar to short period Jupiter Family Comets (JFCs)
- Studying Damocloids may provide insight on HFC nuclei.
- Several Damocloids have exhibited cometary activity but small sample.

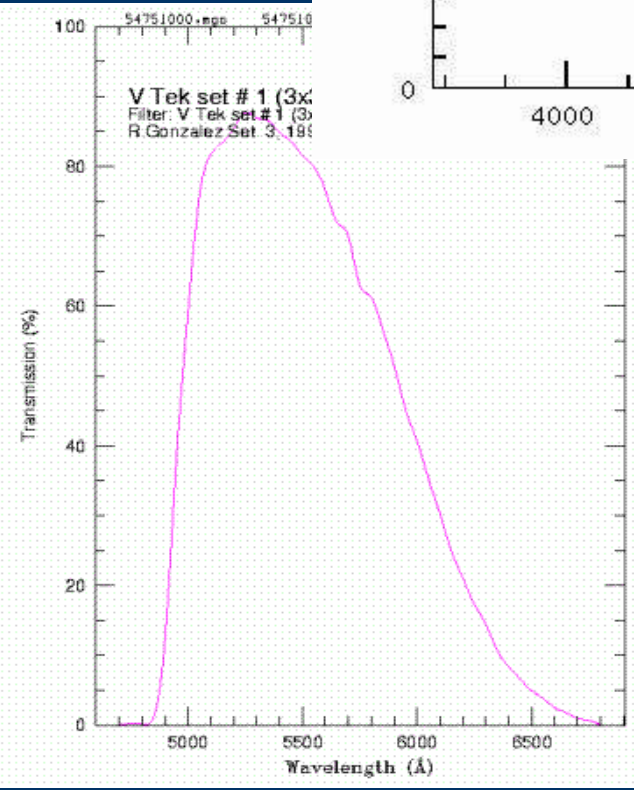
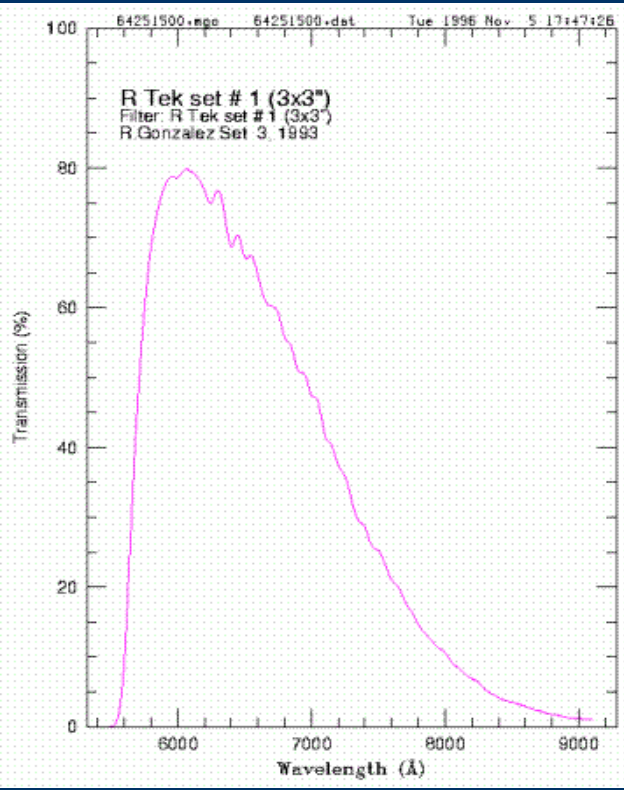
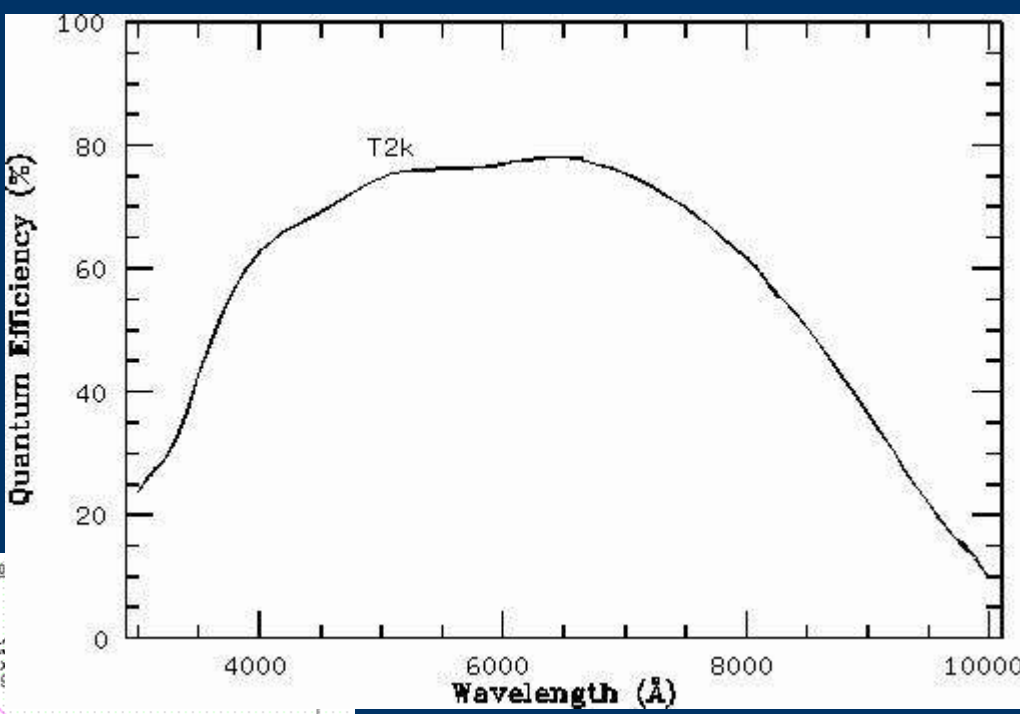


Observations



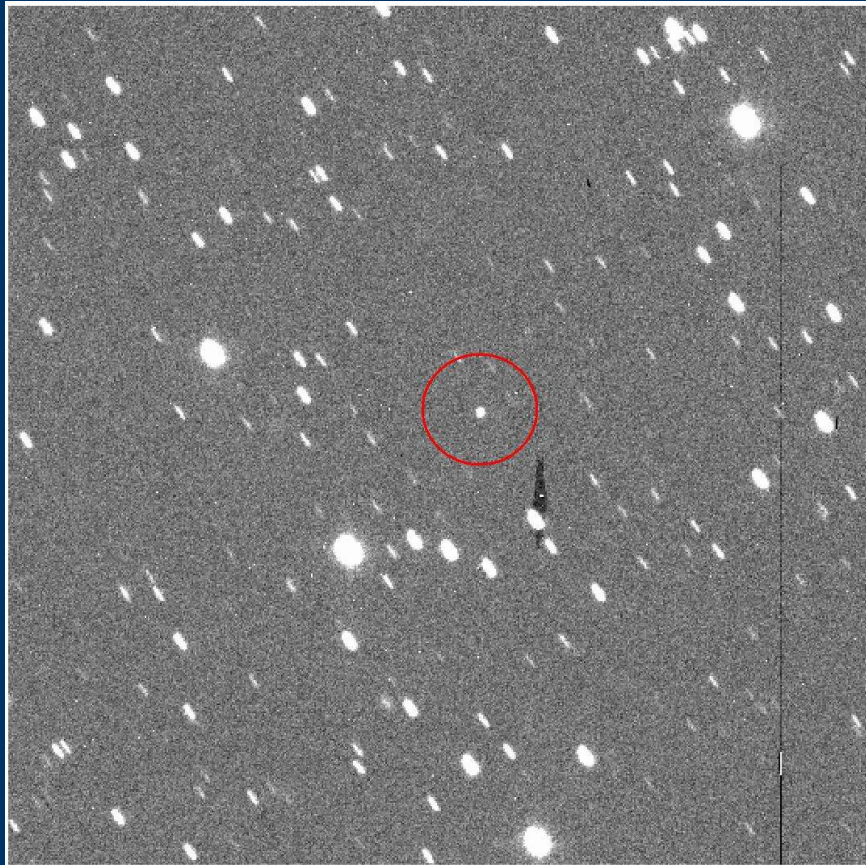
0.9-m and 0.4-m at CTIO

- Johnson-Kron-Cousins BVRI observations w/ 0.9-m Cassegrain SMARTS telescope at the Cerro Tololo Inter-American Observatory (CTIO), Chile, from October 14-20th, 2003
- Thinned, back-illuminated, 2048x2046 Tektronix QUAD CCD with AR coatings to improve performance in near-IR
- f/13.5 Cassegrain focus - Image scale of 0.396"/pixel; Total field size is therefore 13.5'.
- LN2 cooled CCD has better than 70% quantum efficiency at $\lambda \sim 0.7\mu\text{m}$ (Walker, 2000).



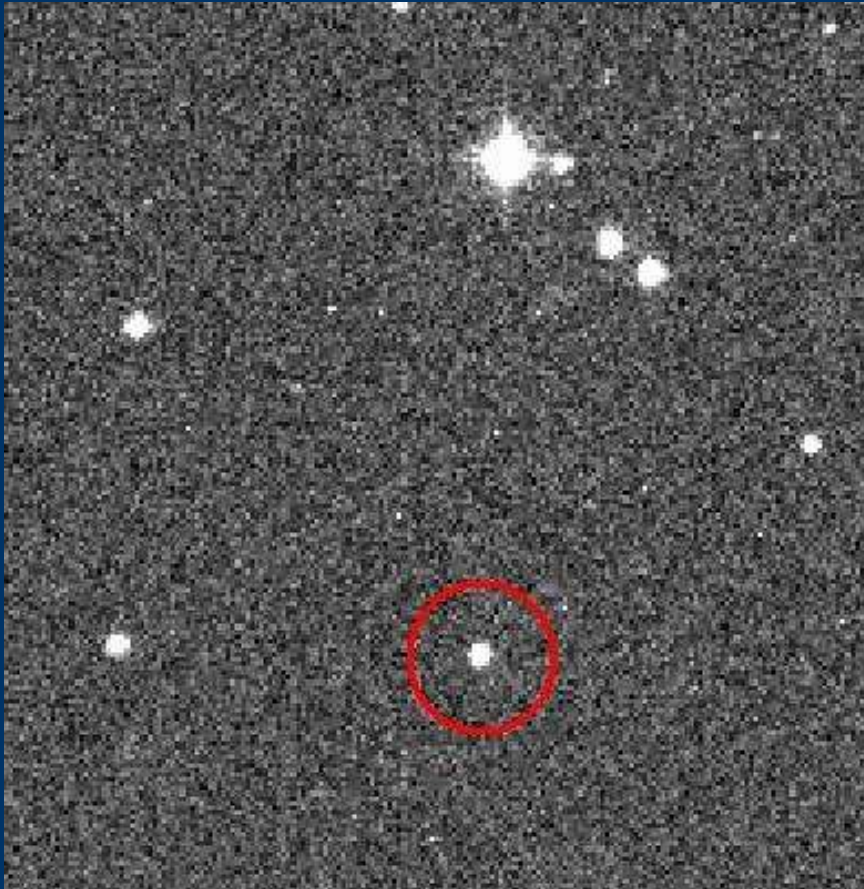
(Source: A. Walker,
R. Gonzalez, CTIO)

Comet C/2002 CE₁₀ (LINEAR)



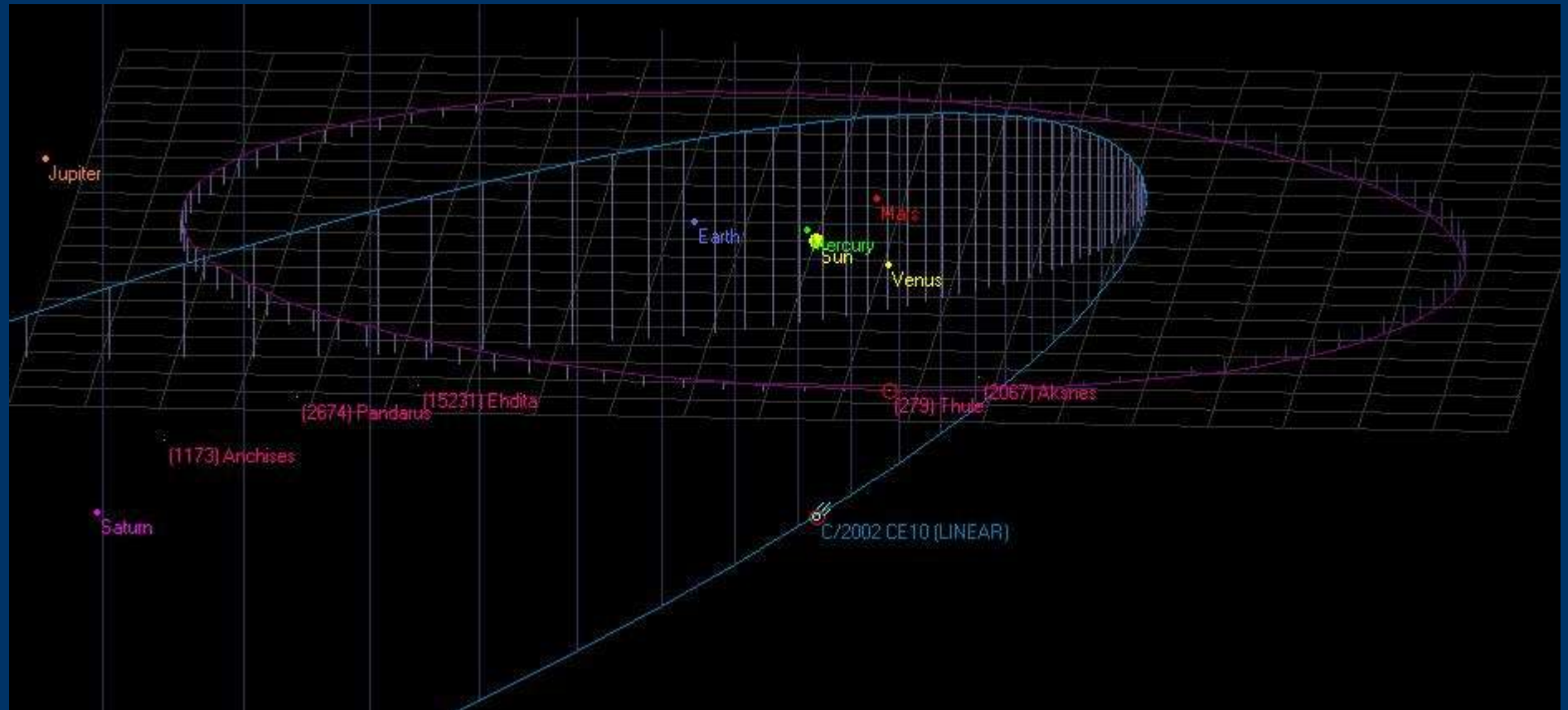
- Period = 30.8 y
- Semi-major axis = 9.81 AU
- Eccentricity = 0.7914
- Inclination = 145.45 deg
- Perihelion = 2.04 AU
- On Oct. 18th 2003 $r = 2.39$ AU, $d = 1.94$ AU, $ph. = 23.8$ deg
- Was classified as an asteroid of the Damocloid family based on orbital elements. Found to exhibit faint tail (Takato et al, 2003)
- Theory that Damocloids are dead Halley Family Comets (Asher et al, 1994) – support – need data on comet nucleus

279 Thule



- Period = 8.84 y
- Semi-major axis = 4.277 AU
- Eccentricity = 0.012
- Inclination = 2.338 deg
- Perihelion = 4.224 AU
- On Oct. 18th 2003 $r = 4.317$ AU, $d = 3.329$ AU, $ph. = 2.0$ deg
- Large main belt asteroid
- D type asteroid – redder than most other asteroids. Thought due to “super carbonaceous chondrites” caused by lower heating (Vilas et al, 1985)
- Interesting features in absorption spectrum (Lagerkvist et al, 1990) – not known asteroidal or atmospheric feature
- Only 4:3 resonance with Jupiter

Orbits of CE10 and Thule



Outline of Image Reduction Steps

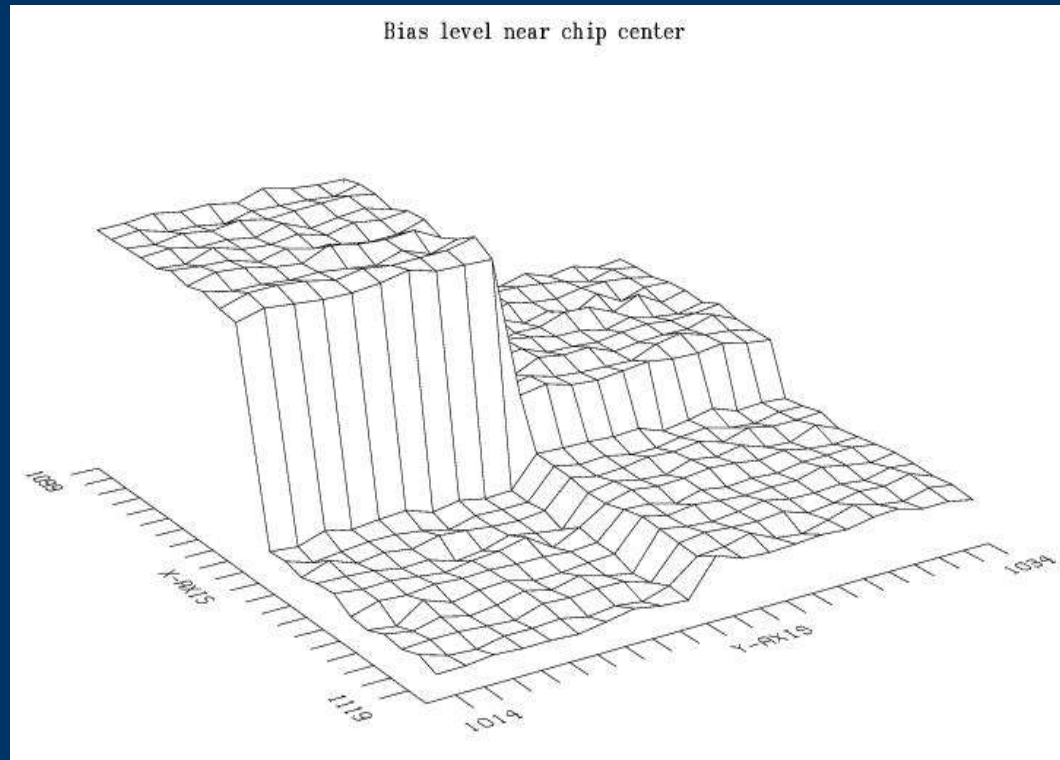
- Trimming
- Overscan Correction
- Bias Subtraction
- Flat-fielding

All Sky Photometry

- Removing sky background
- Counting and instrumental magnitudes
- Photometric Calibration onto JCK system

Apparent Magnitudes! (*not even near done*)

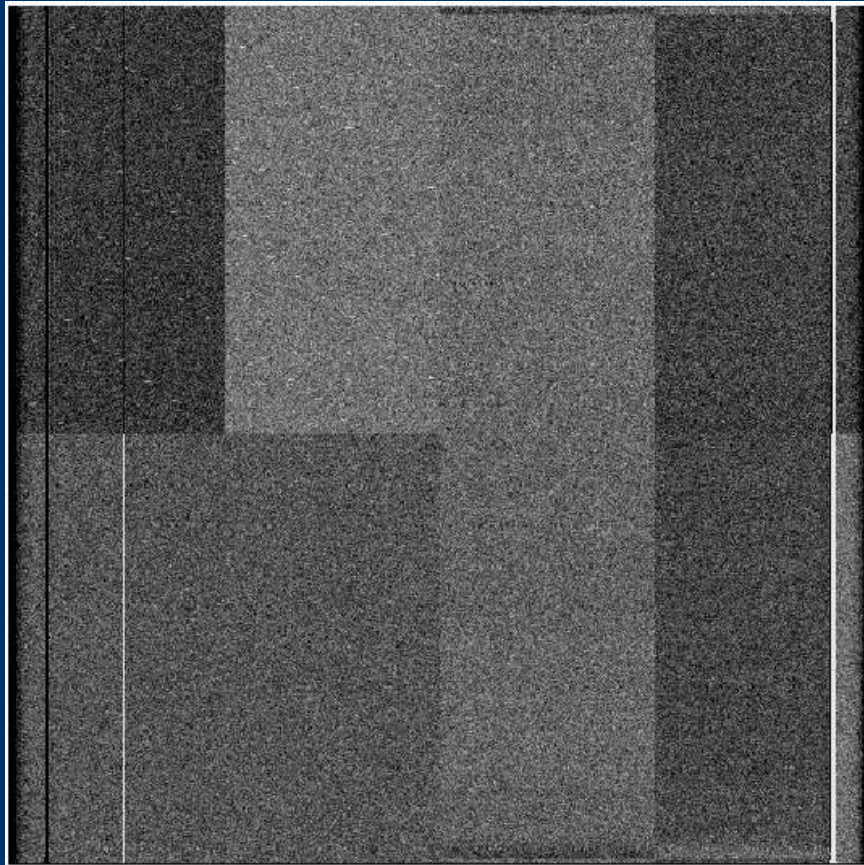
Bias Subtraction



(635, 553, 521, 505 ADU) – QUAD Mode

- Remove electrical background noise associated with CCD readout and correct for voltage differences of CCD gates
- Gate voltage acts as an offset from zero for the level at each pixel.

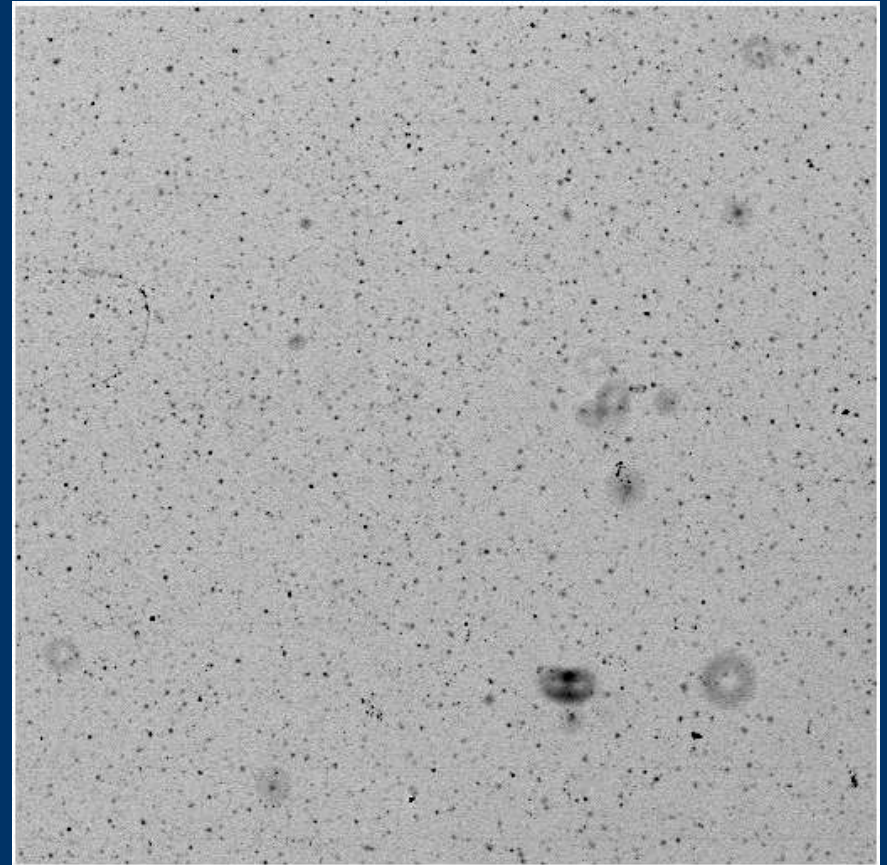
CCD Readout and Bias Correction



- CCD readout through four separate amplifiers
- Significantly reduces readout time.
- Voltage applied to the gates on the CCD by each of the 4 amplifiers is slightly different.
- Depends on temperature, column address, telescope position “and who knows what else.” (Massey, 1997)
- Average 10 bias frames to produce a master bias – estimate bias level of a column from the overscan region and use master bias to correct for bias of each pixel.

Flat Fielding

- Normalize variations in pixel response across CCD
- Correct for dust and dirt (donuts) on telescope mirror
- Sky-flats with uniform sky at twilight in BVRI
- Causes dramatic improvement in SNR.

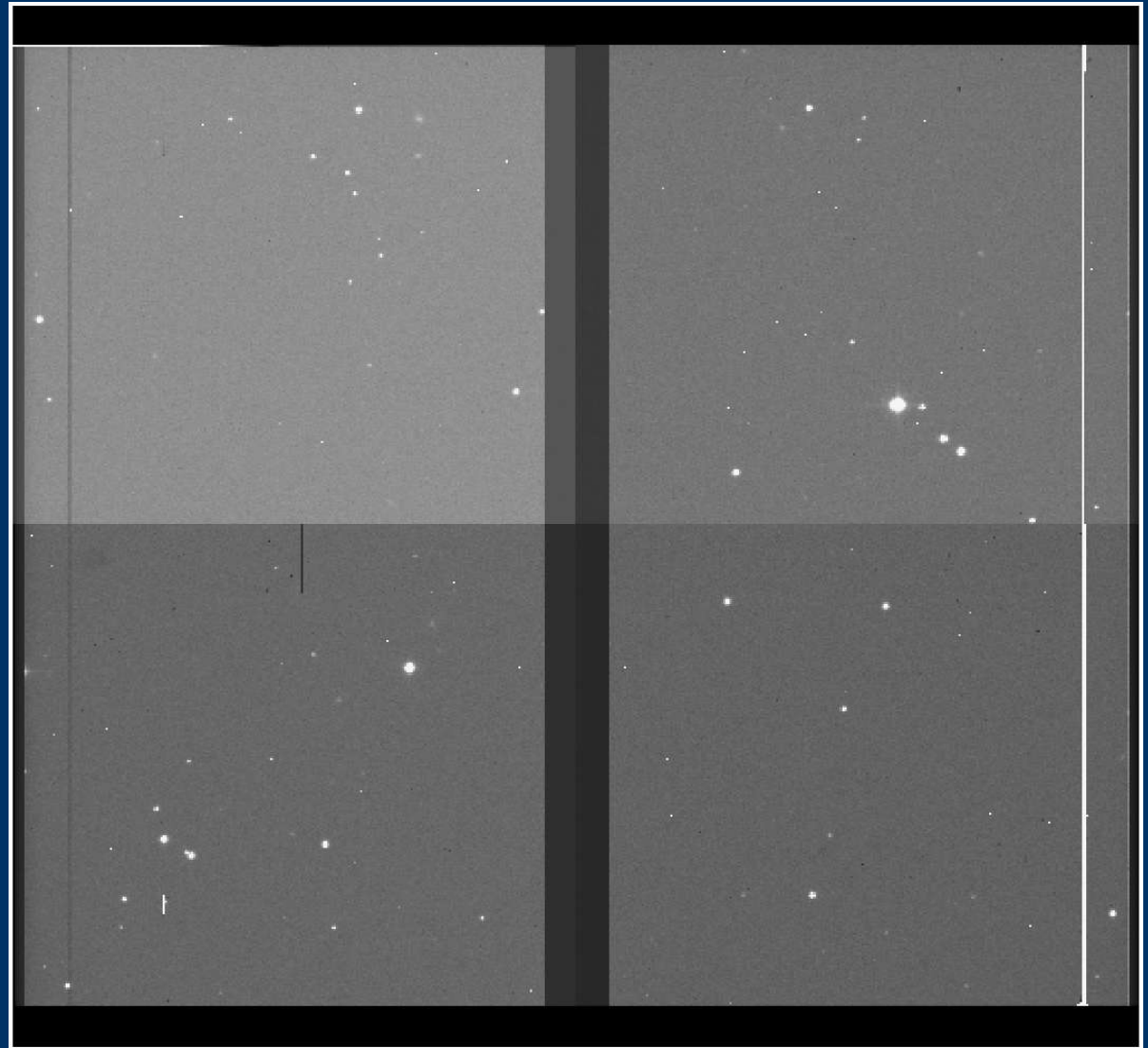


Before

Trim region at top and bottom

Overscan bar at image center

Variations in background and pixel response cause different regions to be different shades of grey



[OTZF]

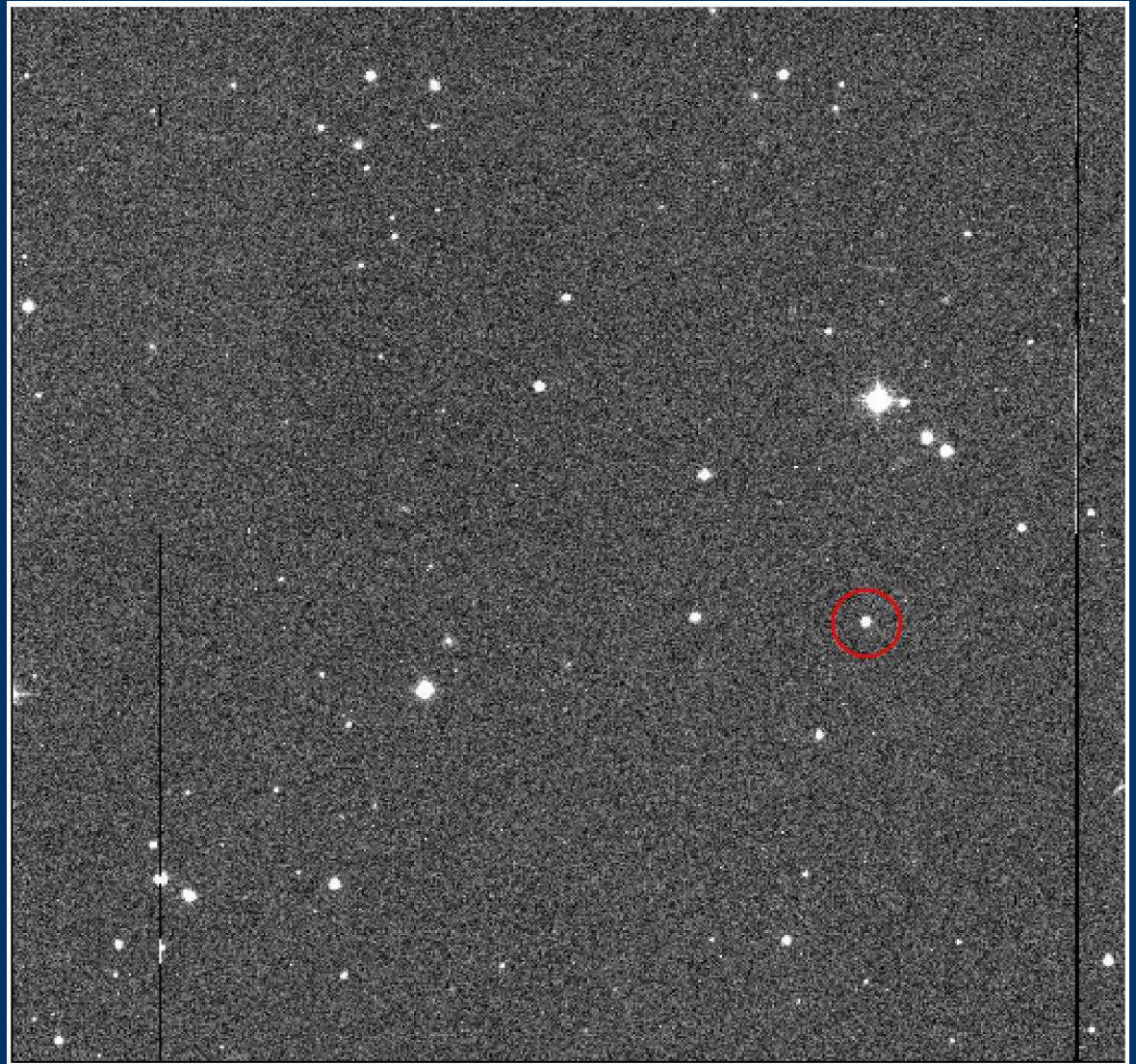
Trimmed

Bias level estimated and removed

Each frame flat fielded with its “master sky-flat” for the night

Response is uniform

~1GB data per night =
Computationally intensive



The Magnitude Equation

$$M_A - M_B = -2.5 \log \left(\frac{I_A}{I_B} \right)$$

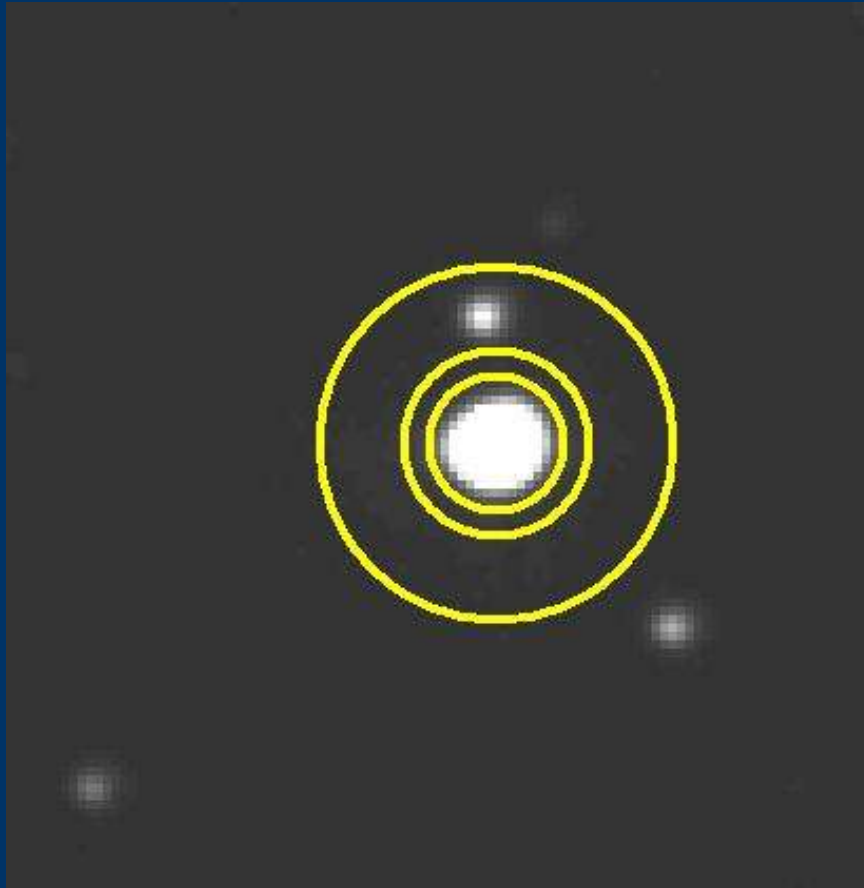
Log scale for intensity, created by Hipparchus

5 magnitude difference corresponds to a ratio of intensities of 100. can be used to ratio distances as intensity varies as inverse-square of distance.

Objects have different intensity at different wavelengths - cited for different wavelength bands such as BVRI. Color index is a difference between magnitudes in the V and the R band. As differences in magnitude are ratios they are independent of changes in distance and other factors.

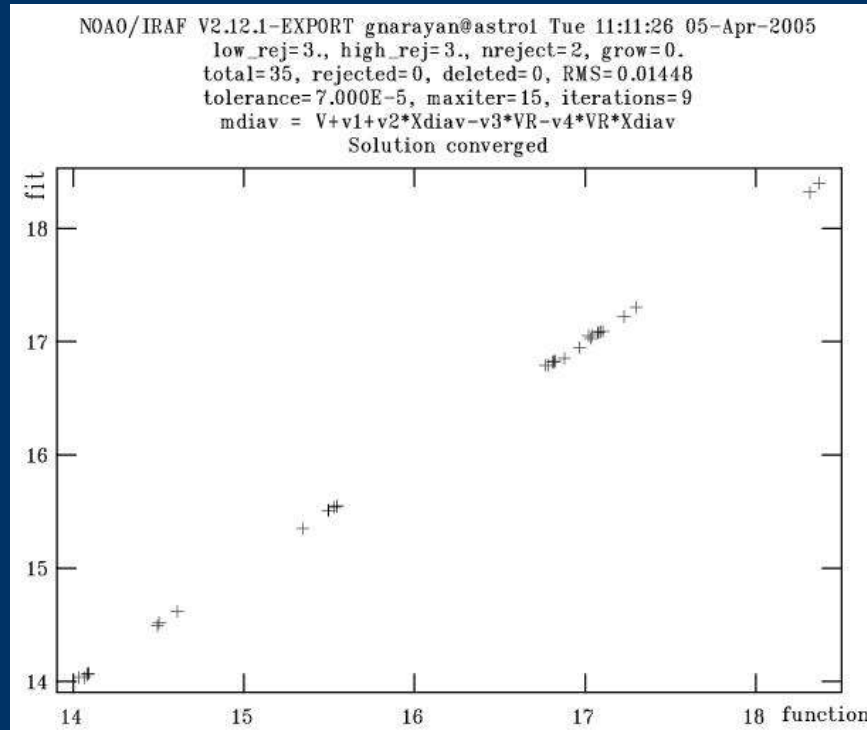
Aperture Photometry

(Source: Hereford AZ Observatory)



- Estimate position of center
- Calculate position through marginal 'x' and 'y' distributions
- Use a fixed aperture to determine “counts” from object
- Use a ring around aperture to determine median level of background sky per pixel
- Subtract out background sky contribution from object counts
- Normalize to unit time
- Instrumental magnitudes and error
- We need to account for filter differences and the atmosphere

Photometric Calibration



- Instrumental Magnitudes calibrated onto Johnson-Kron-Cousins UBVRI using observations of faint stars by A. U. Landolt (1992) in each filter (see Table 4.3, 4.4)
- Convert instrumental magnitudes to apparent magnitudes using magnitude equation with terms for atmospheric extinction, zero point and color coefficient
- Convert apparent magnitudes to absolute magnitudes by accounting for changing distances (easy) and solar phase angle (er...)

$$V(r, \Delta, \alpha) = V(1, 1, 0) + 5 \log(r\Delta) + P(\alpha)$$

Solar phase angle and BHL model

- Without knowing what shape and properties of object surface are we cannot possibly know how the magnitude changes with solar phase – the “phase relation”
- Lumme and Bowell (1981) propose empirical model that fits observations of several (74) low and high albedo asteroids, Moon, Mercury etc.
- Adopted as standard phase relation by International Astronomical Union (Marsden et al, 1986)
- Does IAU relation work for ALL objects – NO (French, L.M. 1987) may not work for C, D and P type asteroids – darker asteroids; appear redder than most outer-belt objects – that were used to derive the IAU phase relation with $G=0.15$ – Go ahead and correct and see what happens.

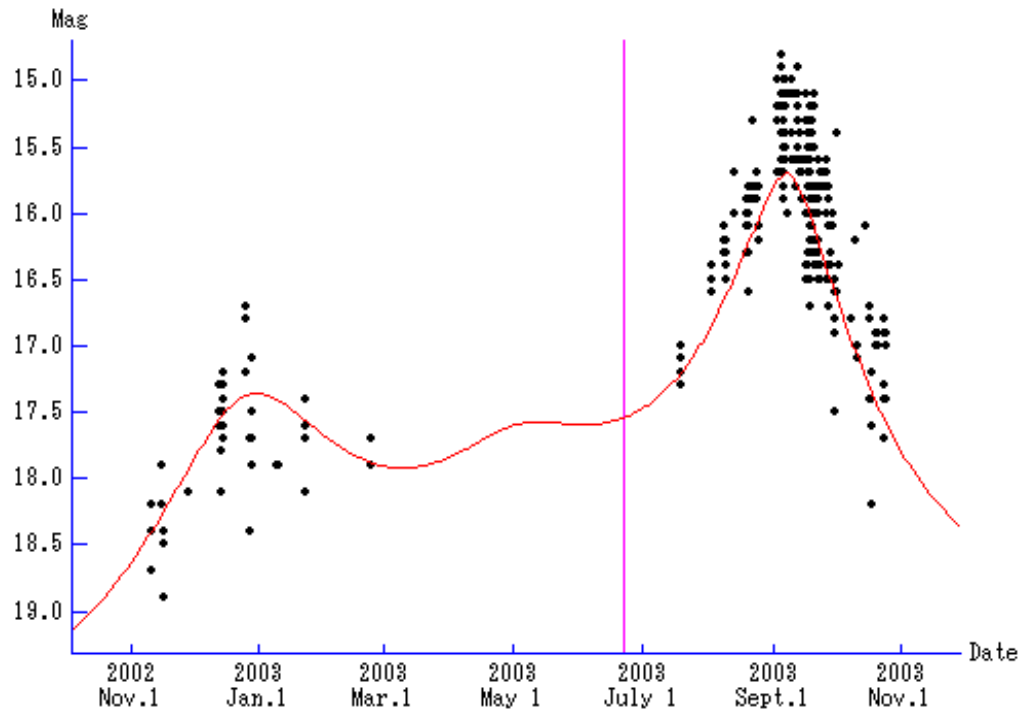
$$P(\alpha) = -2.5 \log [(1-G) \Phi_1(\alpha) + G\Phi_2(\alpha)]$$

$$\Phi_1(\alpha) = \exp[-3.33(\tan(\frac{\alpha}{2}))^{0.63}]$$

$$\Phi_2(\alpha) = \exp[-1.87(\tan(\frac{\alpha}{2}))^{1.22}]$$

Results – C/2002 CE₁₀ (LINEAR)

C/2002 CE10 (LINEAR)



- Observations of Cometary Activity in August – data in October contaminated by coma.
- Our absolute magnitudes from Oct. 2003 in Jan. 2003 (10m Keck) (Jewitt, 2005) but do agree with observations in Aug. 2003 (UH 2.2m)
- $V(1,1,0) = 13.11 \pm 0.01$ $V-R = 0.54 \pm 0.03$ (this study)
- $V(1,1,0) = 13.06^* \pm 0.04$ $V-R = 0.53 \pm 0.02$ (2003, Aug 28) (Jewitt, 2005)
- Interestingly, color index does not change from Jan-Oct.

(Source: Subaru data, S. Yoshida)

Phase Dispersion Minimization

- Algorithm to determine rotational period (Stellingwerf, 1978)
- Fold data to assumed lightcurve, based on calculated rotational phase for assumed period, and bin on rotational phase.
- Repeat for several periods. Data that minimizes ratio of scatter in all bins to overall scatter is minimum period.

$$\sigma^2 = \frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N - 1}$$

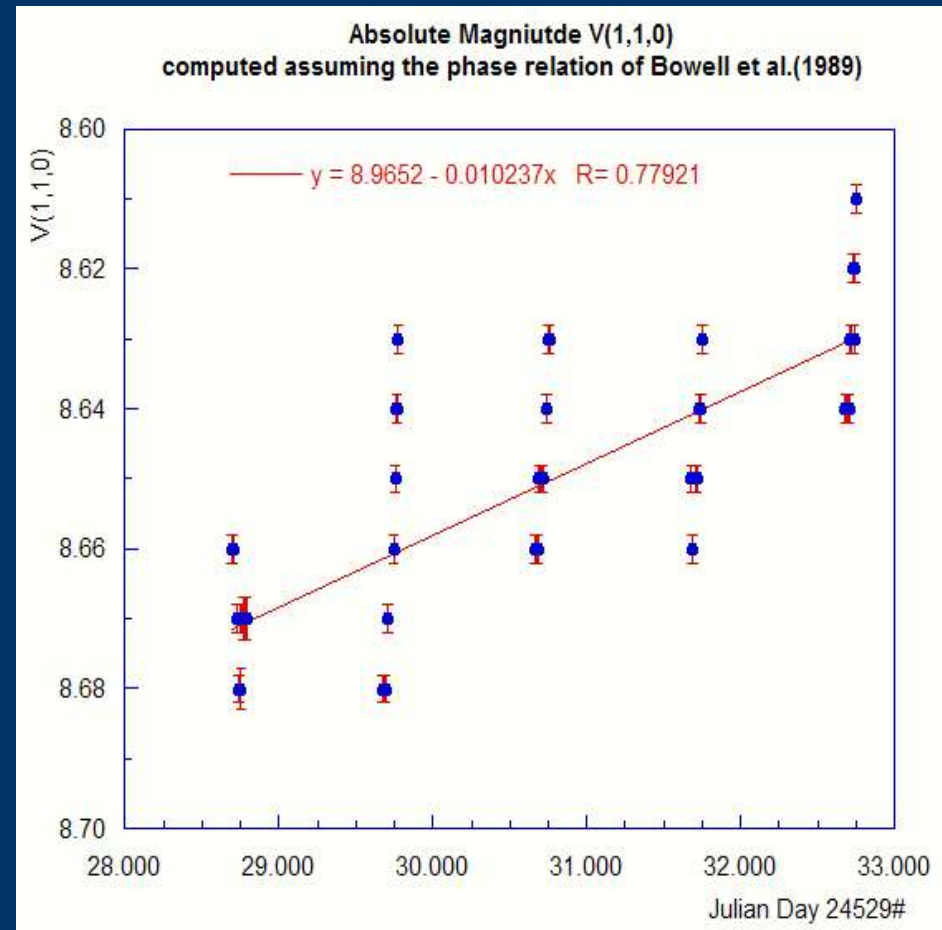
$$s^2 = \frac{\sum_{j=1}^M (n_j - 1) s_j^2}{\sum_{j=1}^M n_j - M}$$

$$\phi_i = t_i \bmod (\Pi)$$

$$\Theta = \frac{s^2}{\sigma^2}$$

Results for 279 Thule

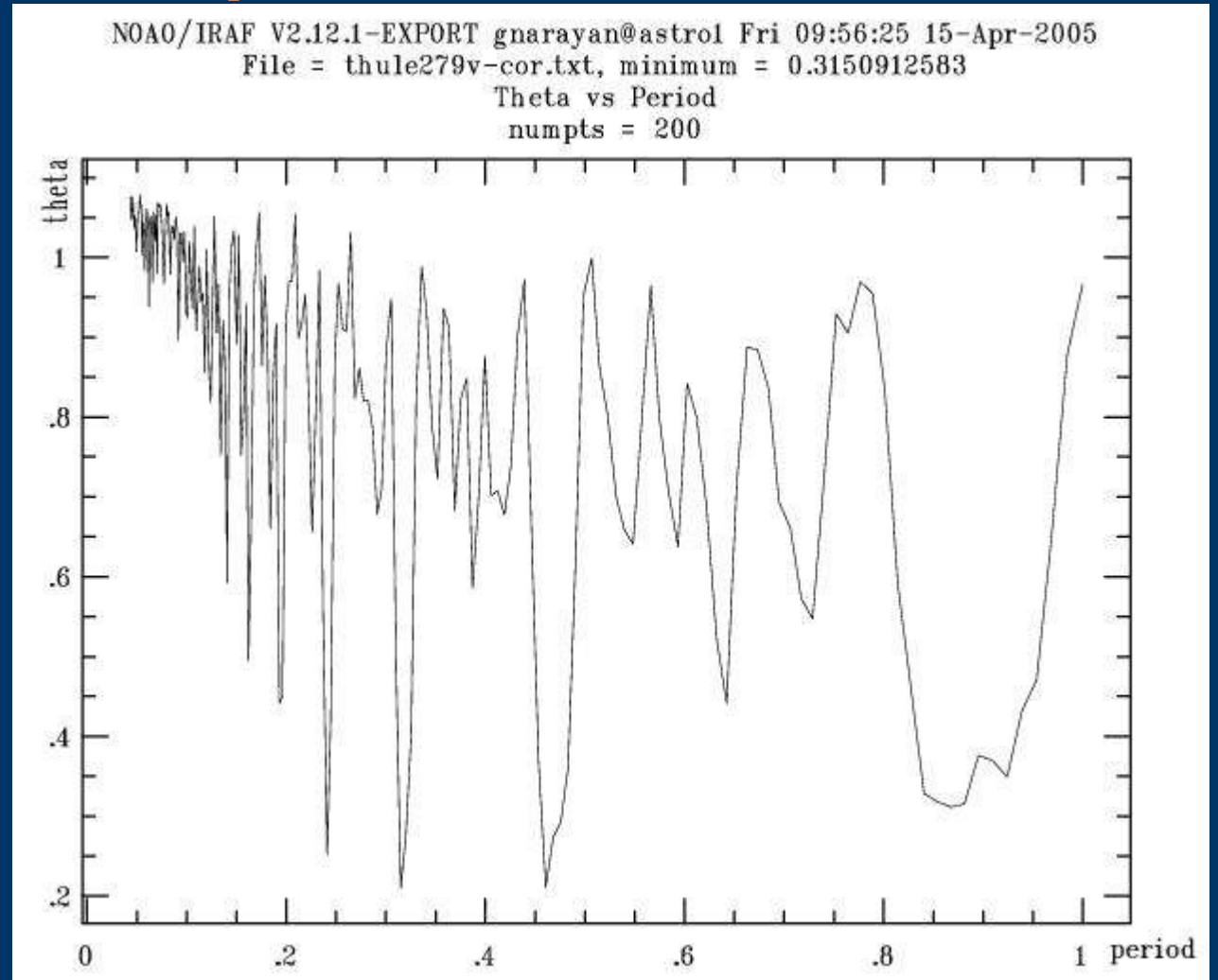
- Previously observed 1984 Aug 21-23 (ESO) near opposition (Zappala et al, 1989)
- $V(1,1,0) = 8.66 \pm 0.01$ V-
 $R = 0.44 \pm 0.03$ (this study – IAU solar phase relation) Rotation Period = 7.59 hrs $\Delta M = 0.05 \pm 0.01$ (one night variation)
- $V(1,1,0) = 8.57$ (Zappala – using IAU solar phase relation) Rotation period = 7.44 hrs $\Delta M = 0.06 \pm 0.01$ (from rotational light curve)
- Increasing trend in brightness – artifact of incomplete rotational phase coverage or is the IAU solar phase correction too large for this object?



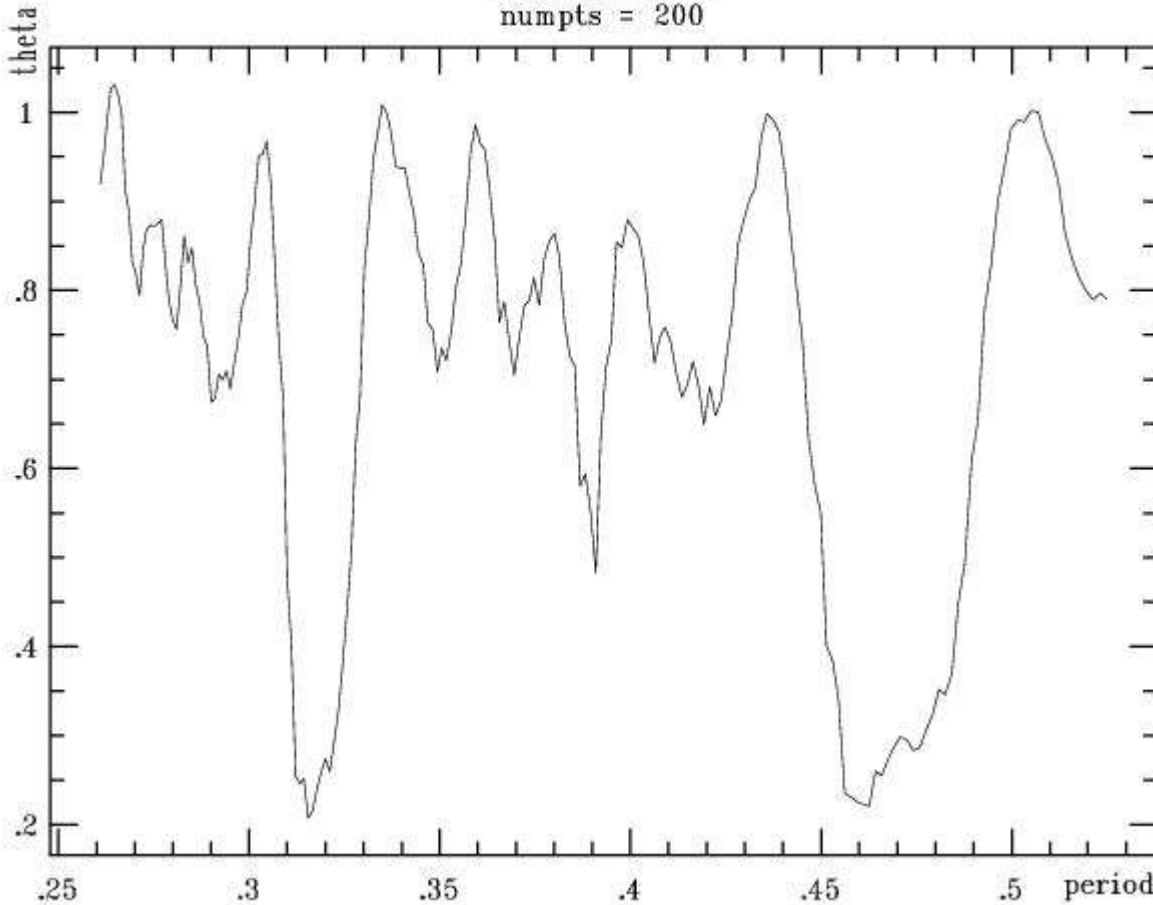
Results (contd.)

PDM scans find minimum period at 7.59 hrs.

Other comparable periods are alias of minimum period caused by insufficient coverage of rotational phase - apparent pattern in periods $3/4$; $3/3$; $3/2$



NOAO/IRAF V2.12.1-EXPORT gnarayan@astro1 Fri 09:57:07 15-Apr-2005
File = thule279v-cor.txt, minimum = 0.3155020796
Theta vs Period
numpts = 200



Since PDM bins on rotational phase it is virtually impossible to have theta be zero, since there is always some scatter in the bins.

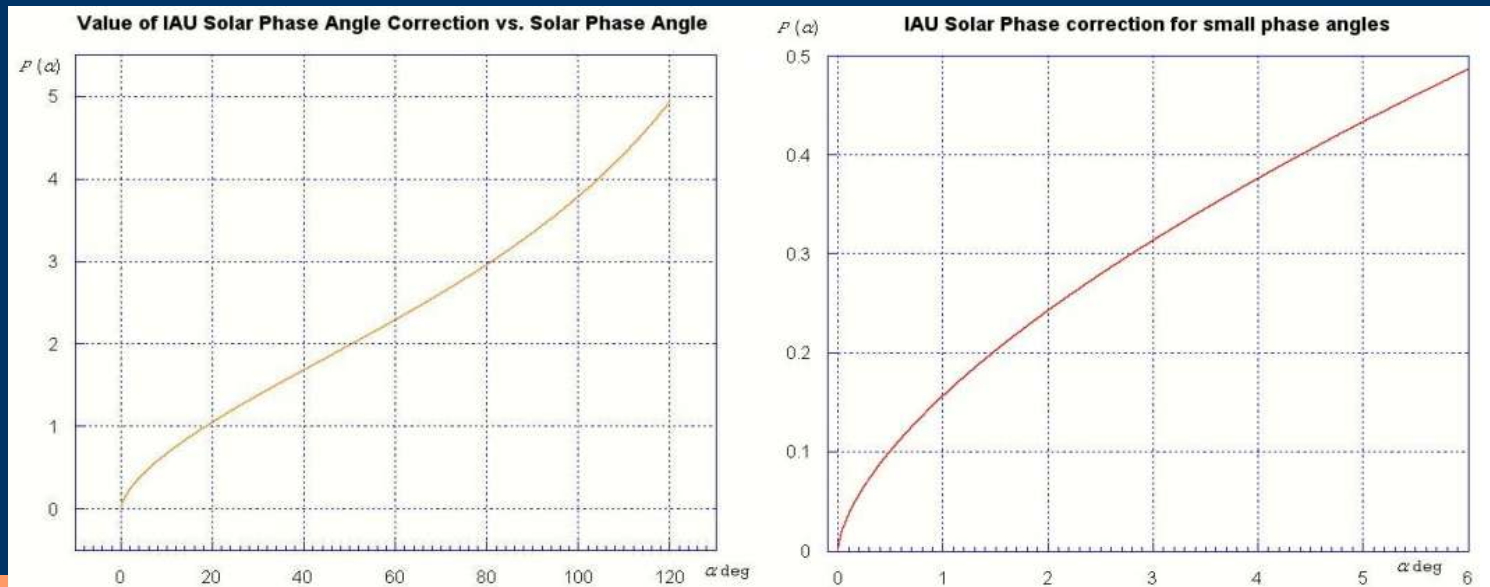
Does not provide an easy means to determine an error – examine FWHM of the dip in the theta at the minimum period. Not strictly an error in the period.

Input times are accurate to a second.

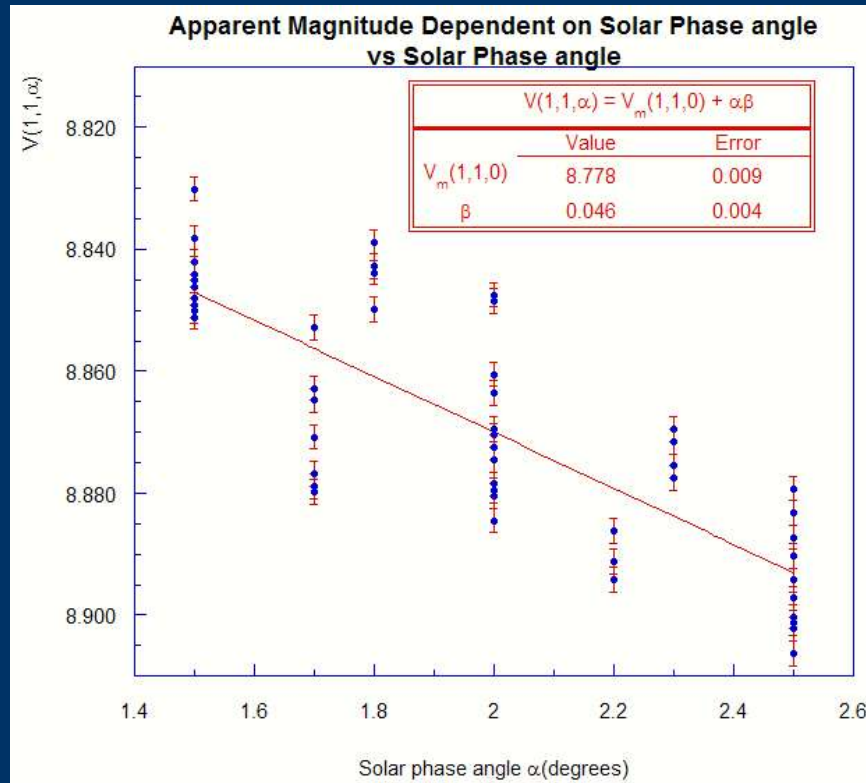
Get more data and determine period with DFT.

Opposition Effect

- Observed non-linear change in apparent magnitude when object is near opposition (Solar phase angle between 0 and 5 degrees)
- Since BHL relation is empirical, and many asteroids do show opposition effect, the model does include it.
- **NOT SEEN** in 1173 Anchises (C or P type) and 2674 Pandarus (D type) observed by French (1987) - IAU relation may not hold for “red” objects. Linear phase relation could fit data.



Results (contd.)



- Apparent magnitude does increase with phase angle.
- No non-linear surge seen – insufficient solar phase coverage. Apparent magnitude fits linear phase relation also. Inconclusive – further study required.
- Can improve our data if rotational component of lightcurve (vertical scatter) removed but insufficient rotational phase coverage to determine lightcurve shape – only period.
- Very interesting object for future study.

Future Observations

THE OTHER COAST



Get more data on both objects, preferably with larger aperture telescope to reduce integration times, minimize trailing etc. Thule is easy to study because of circular orbit and low magnitude. More studies of P and D type asteroids to determine if these objects show opposition effect. Tell more about surface texture properties.

Acknowledgments

The author wishes to thank Professor Linda French, for the opportunity to learn from and work with her.

He recognizes that all his Professors in the department have been mentors and guides, and have taught him considerably more than physics. He is very grateful to the department for ensuring that none of the physics classes he needed were earlier than 10AM. He thanks all of his readers for their valuable feedback.

A very special thanks is due to our telops, Edgardo Cosgrove and Arturo Gomez who threatened to throw him off the mountain if the seeing didn't improve. He thanks the tech support provided by Patricio Ugarte and Enrique Schmidt without which we couldn't have recovered from malfunctions on our final night. He extends many thanks to all the other CTIO staff without which none of this would have been possible.

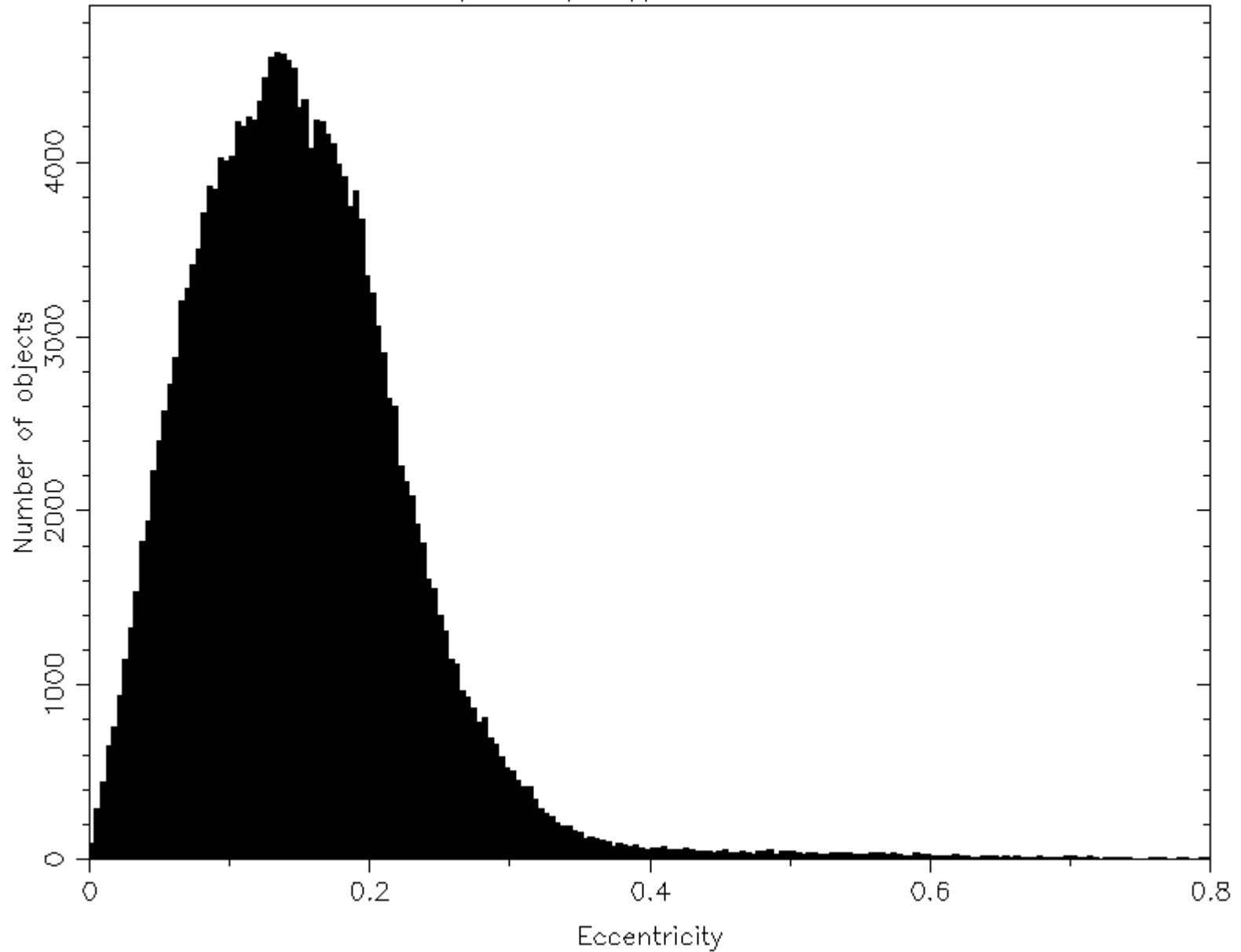
He is very grateful to all his peers for motivating him and waking him up when he wanted to sleep. He apologizes to Robin Johnson, who made the mistake of volunteering to read his thesis to find errors.

He gratefully acknowledges Lisa Ruberstelli and his friends and co-workers at The Coffee Shoppe, for keeping him well caffeinated during his time at Illinois Wesleyan.

He thanks the Provost of Illinois Wesleyan University and the Illinois Wesleyan Faculty Development Fund for supporting this research.

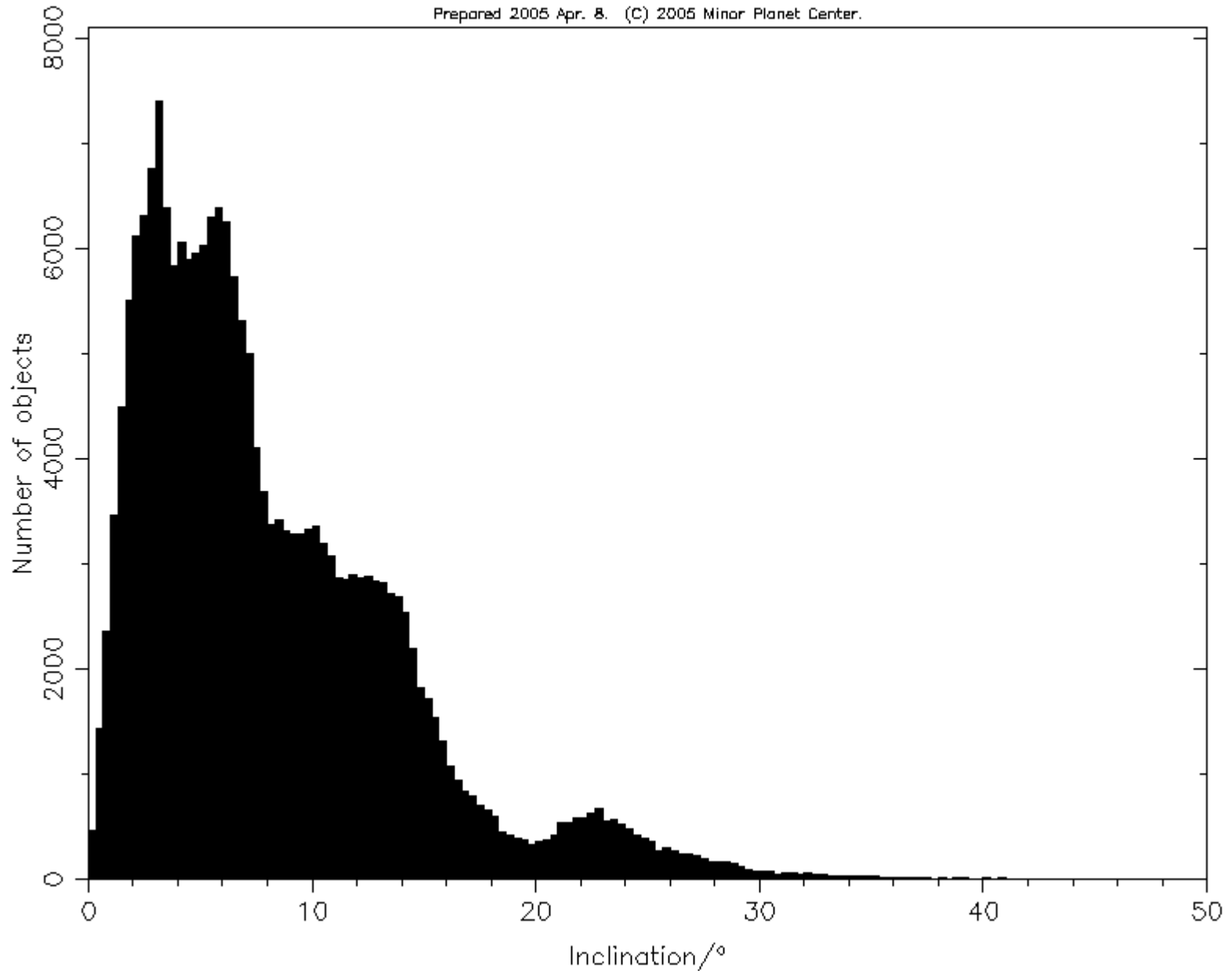
Distribution of the Minor Planets: Eccentricity

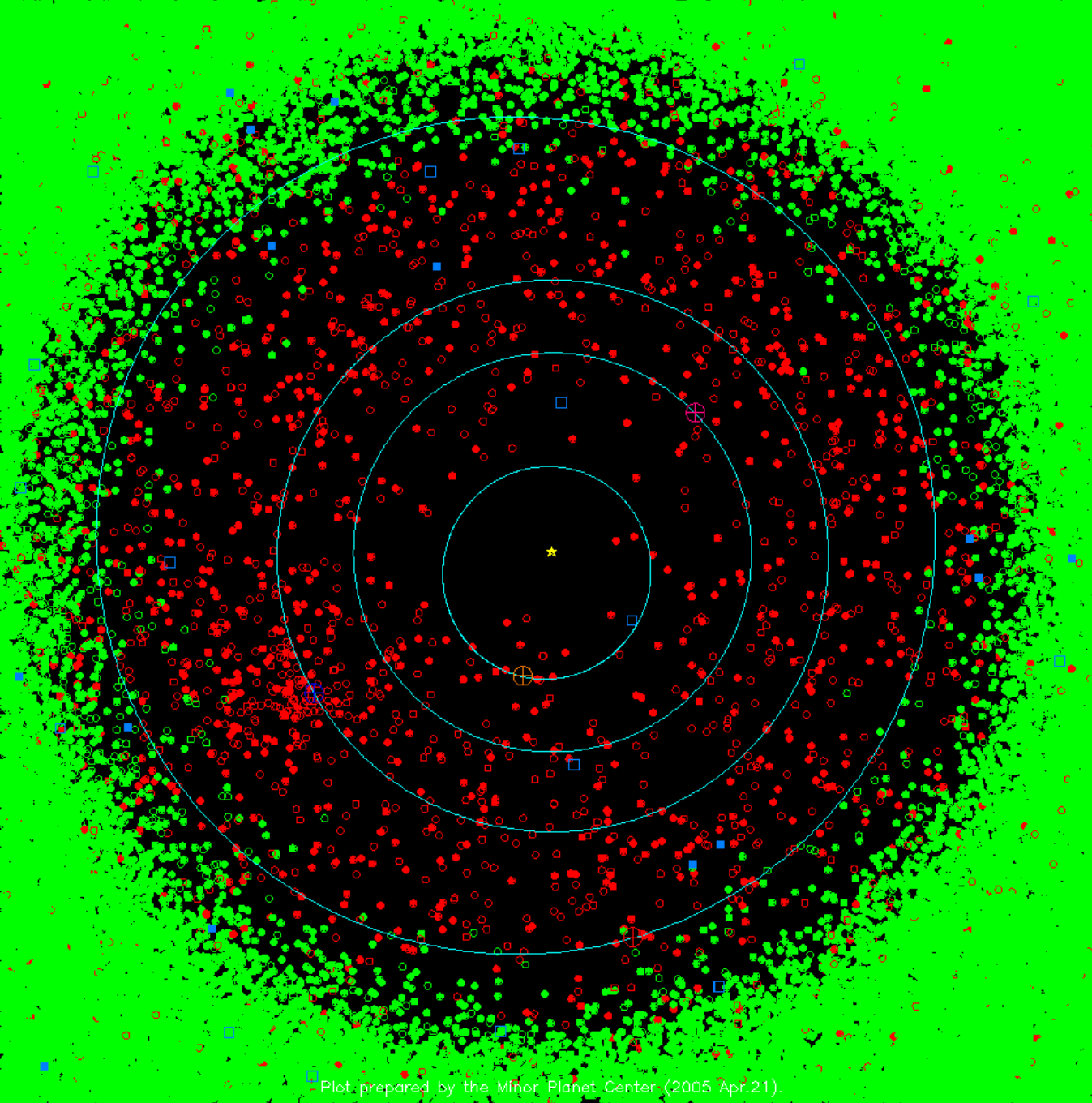
Prepared 2005 Apr. 8. (C) 2005 Minor Planet Center.



Distribution of the Minor Planets: Inclination

Prepared 2005 Apr. 8. (C) 2005 Minor Planet Center.

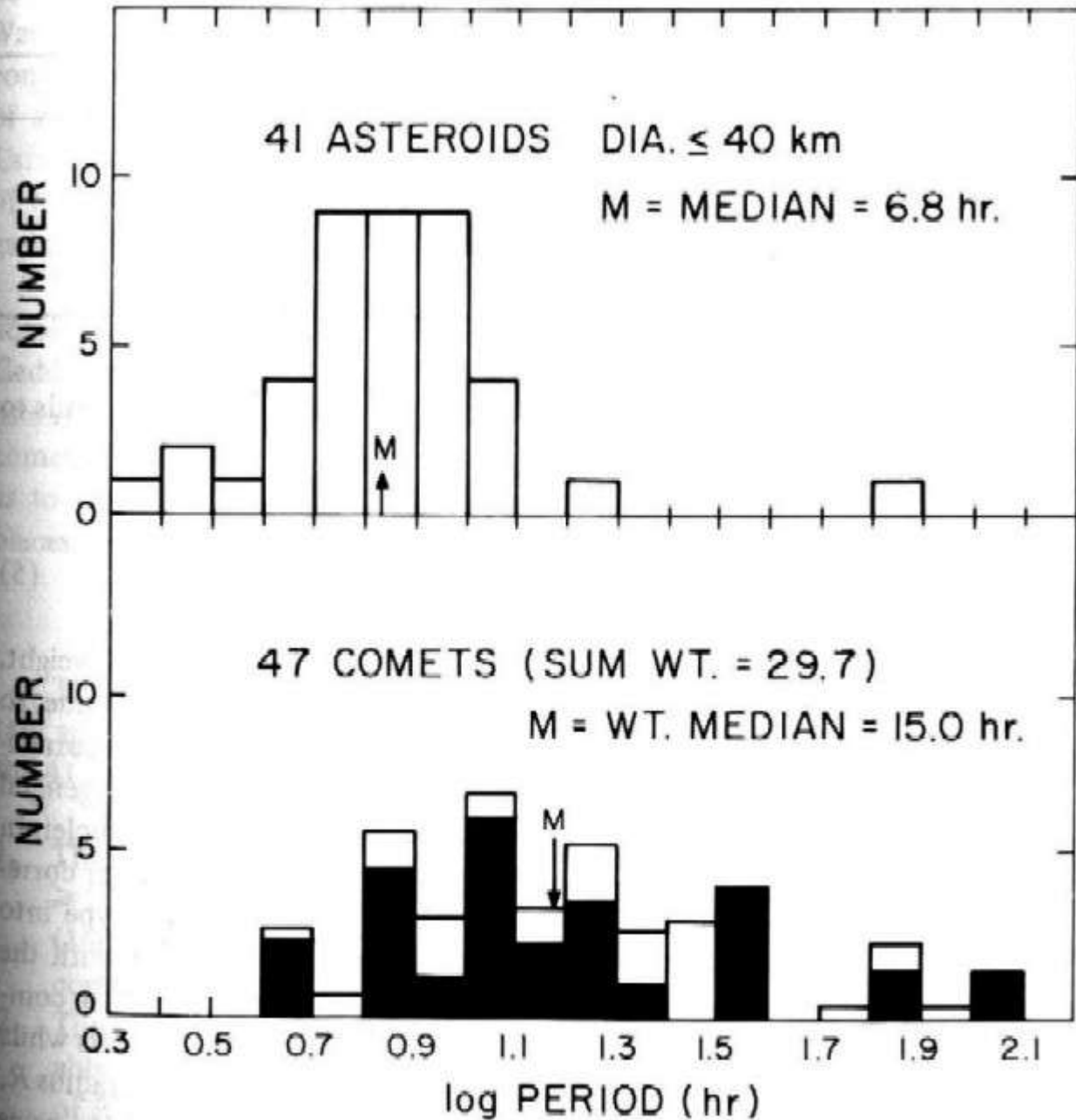




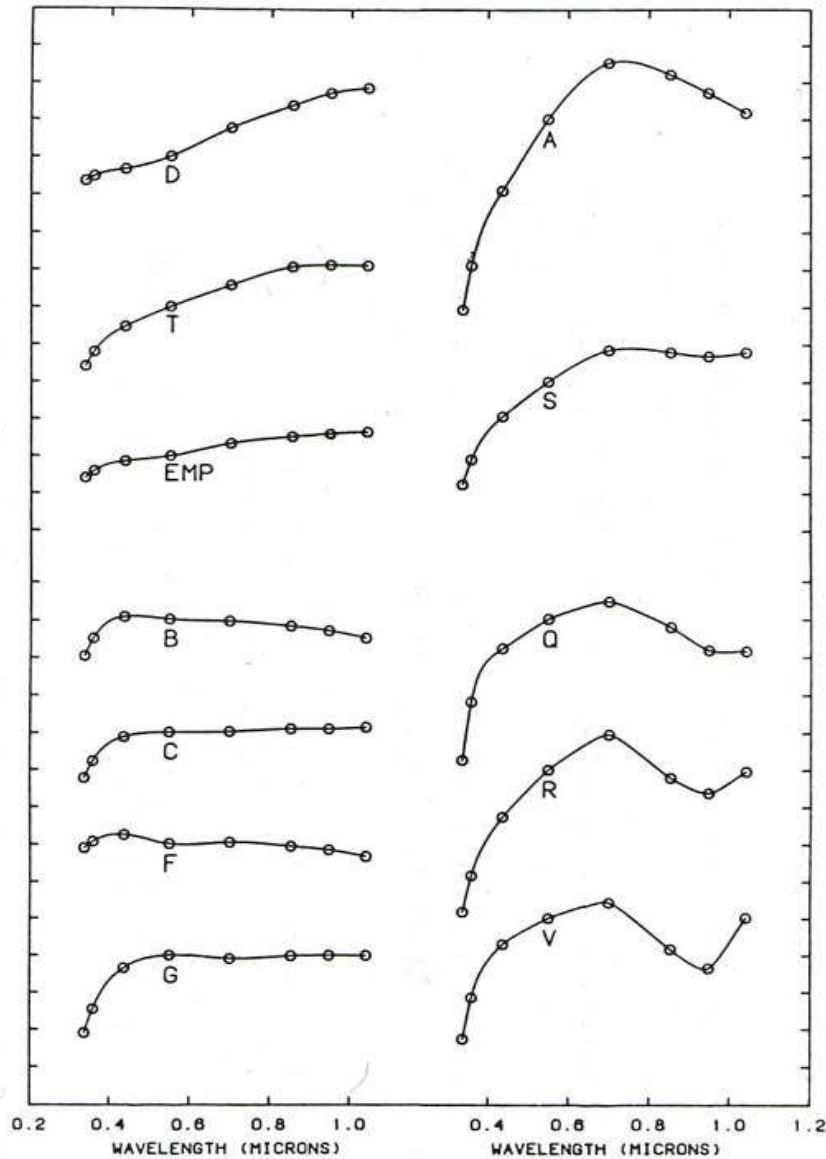
A good reason to study asteroids is found when we examine our local neighborhood. These things move. And suffer gravitational perturbations.

NEAT huh.

(Source: F. L. Whipple)

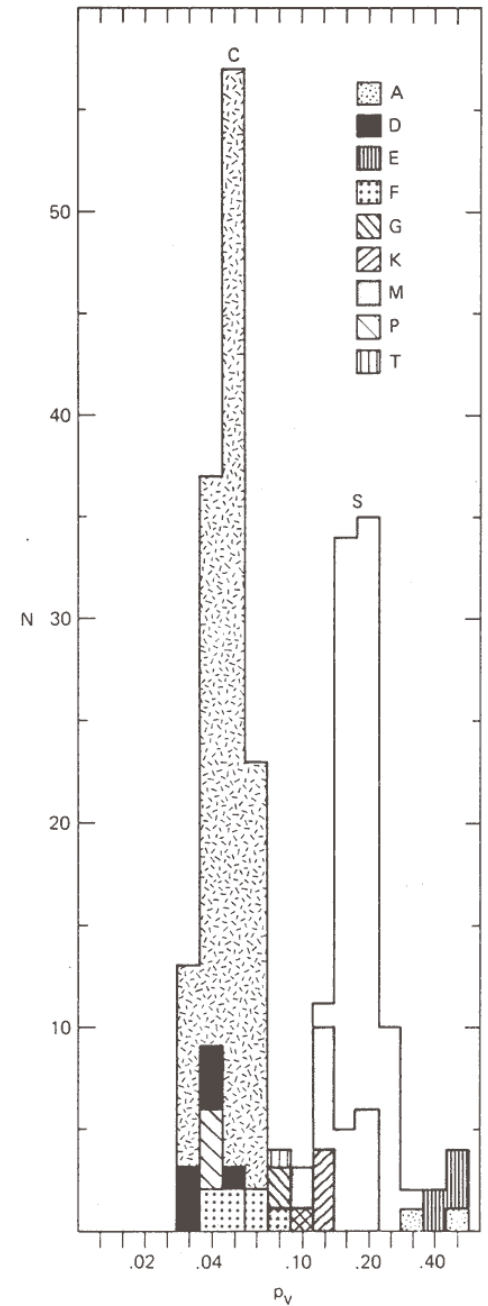


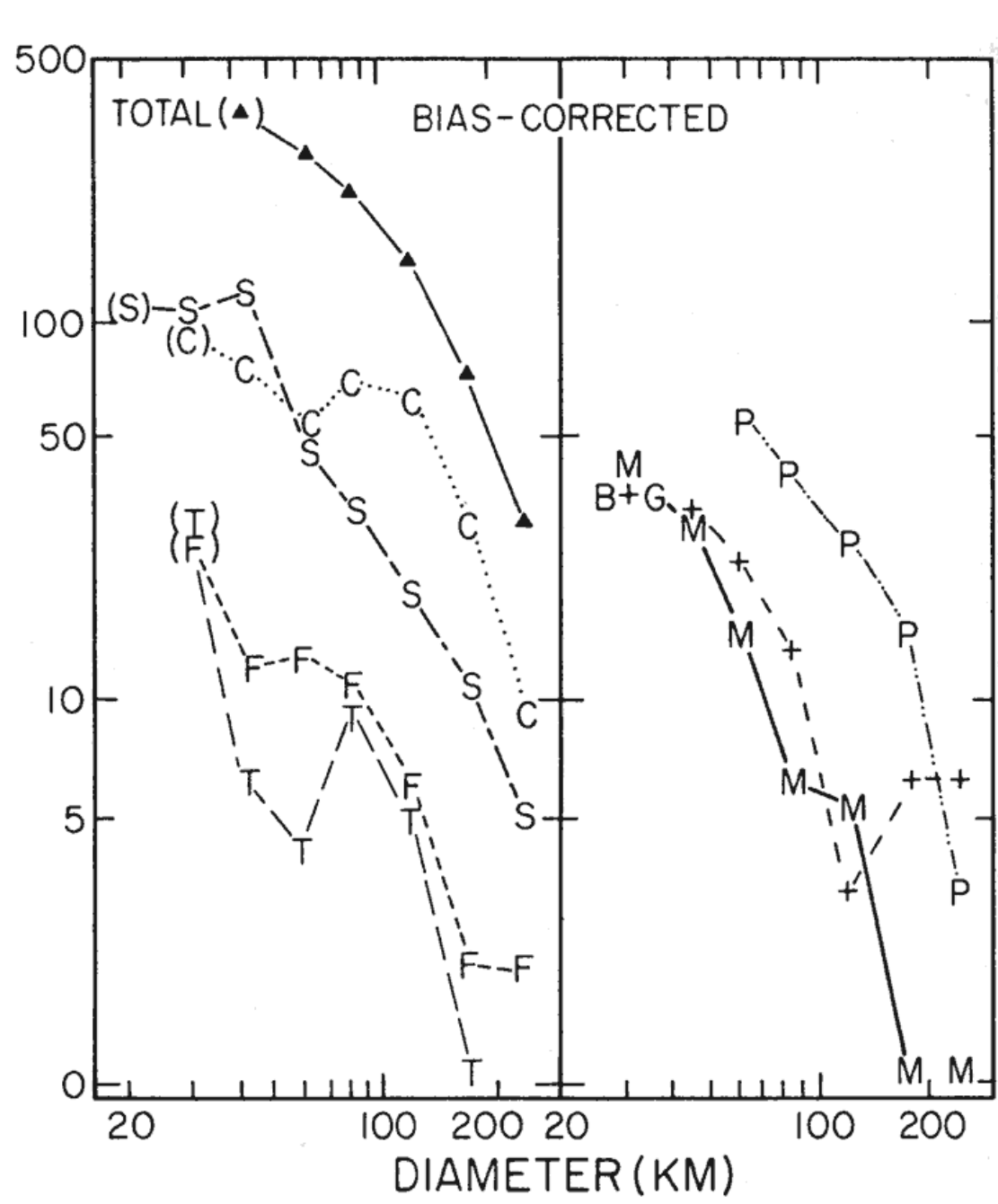
ASTEROID TAXONOMY



Mean reflectance spectra [L] for asteroid taxonomic classes and distribution of albedos [R] – [L] ticks on ordinate are 0.2 magnitudes apart. Spectra is based on Tholen asteroid taxonomic classifications. [R] is based on Tedesco classification.

(Source: [L] Tholen et al; [R] Tedesco et al; 1989, In Asteroids II)





Distribution of sizes based on Tholen asteroid taxonomic classification. (Source: Tholen et al; 1989; Asteroids II)

Magnitude Error – Counting and Shot Noise

- Detection of a photon is a random event and independent of the detection of any other photon – governed by Poisson statistics
 - Standard deviation of Poisson distribution – counting error goes as \sqrt{N} but counts go as N .
 - We cannot remove the \sqrt{N} “shot noise” (unless $N = 0$ which is no signal at all), nor can we stop it from growing with the number of counts.
 - However, **RELATIVE ERROR** goes as $1/\sqrt{N}$ – “examine each frame after acquisition to ensure we have sufficient signal for target objects to perform reliable photometry.”
 - See Fig 4.2 last line under flux for a value of N .
-
-