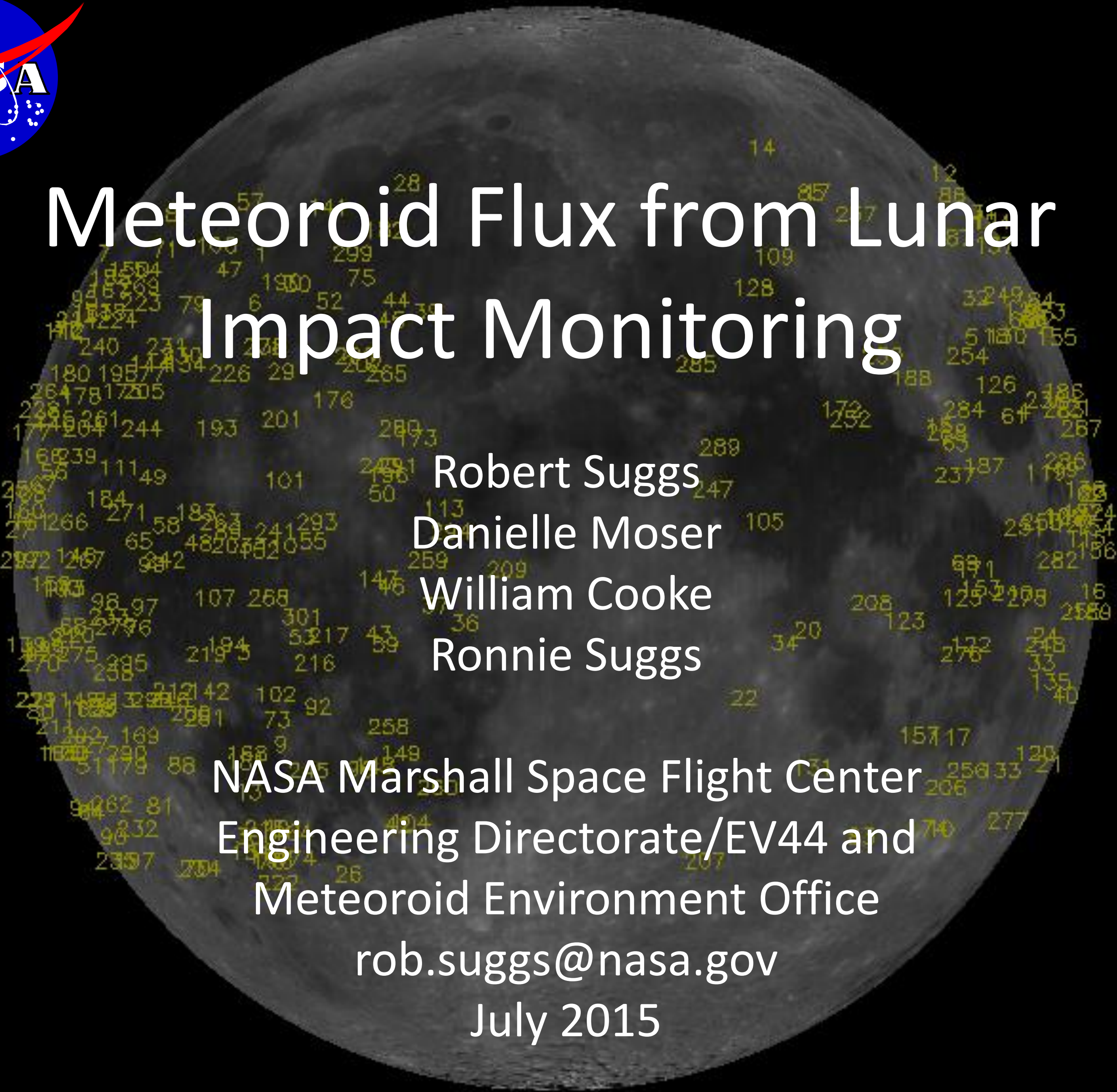

Meteoroid Flux from Lunar Impact Monitoring

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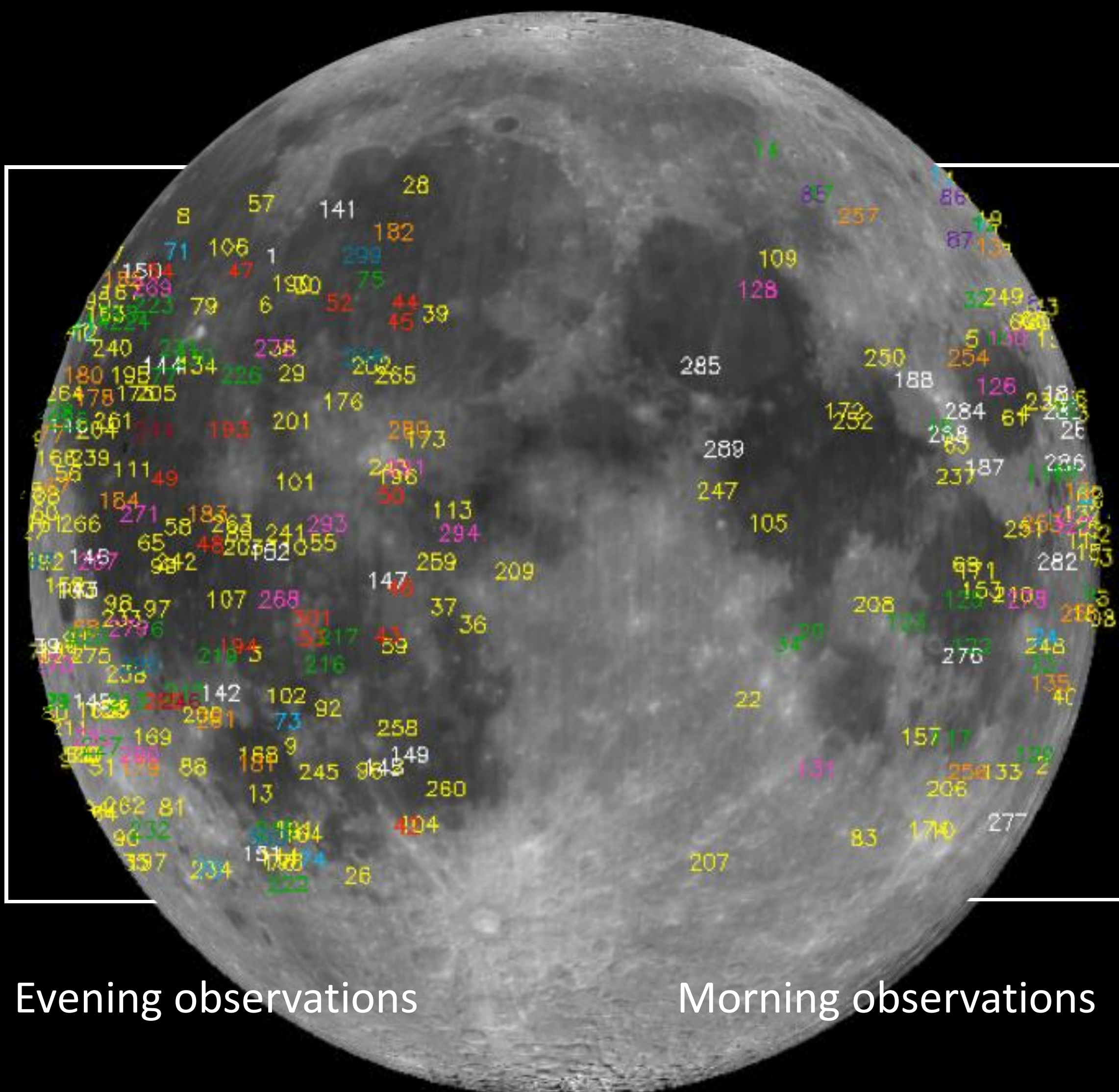
Outline

- Observational Technique
- Photometric Calibration
- Energy Calculation
- Limiting Energy and Mass
- Flux

9 Years of Observations

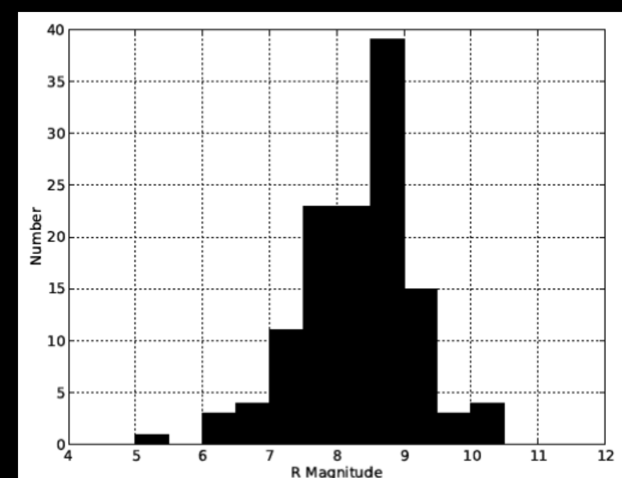
- The MSFC lunar impact monitoring program began in 2006 in support of environment definition for the Constellation (return to Moon) program
- Work continued by the Meteoroid Environment Office after Constellation cancellation
  - Lunar impact monitoring allows measurement of fluxes in a size range not easily observed
- A paper published in Icarus reported on the first 5 years of observations
  - **Icarus:** http://www.sciencedirect.com/science/article/pii/S0019103514002243
  - **ArXiv:** http://arxiv.org/abs/1404.6458

Observation Summary



330+ impacts since 2005

Subset of 126 flashes on photometric nights to 2011
141 hrs evening - 81 flashes
126 hrs morning - 45 flashes
Average: 2.1 hrs/flash
evening/morning = 1.6:1



Photometric error ~0.2 mag

Camera Field of View and Tracking

Approximately 20 arcminutes horizontal, 3.8×10^6 km^2

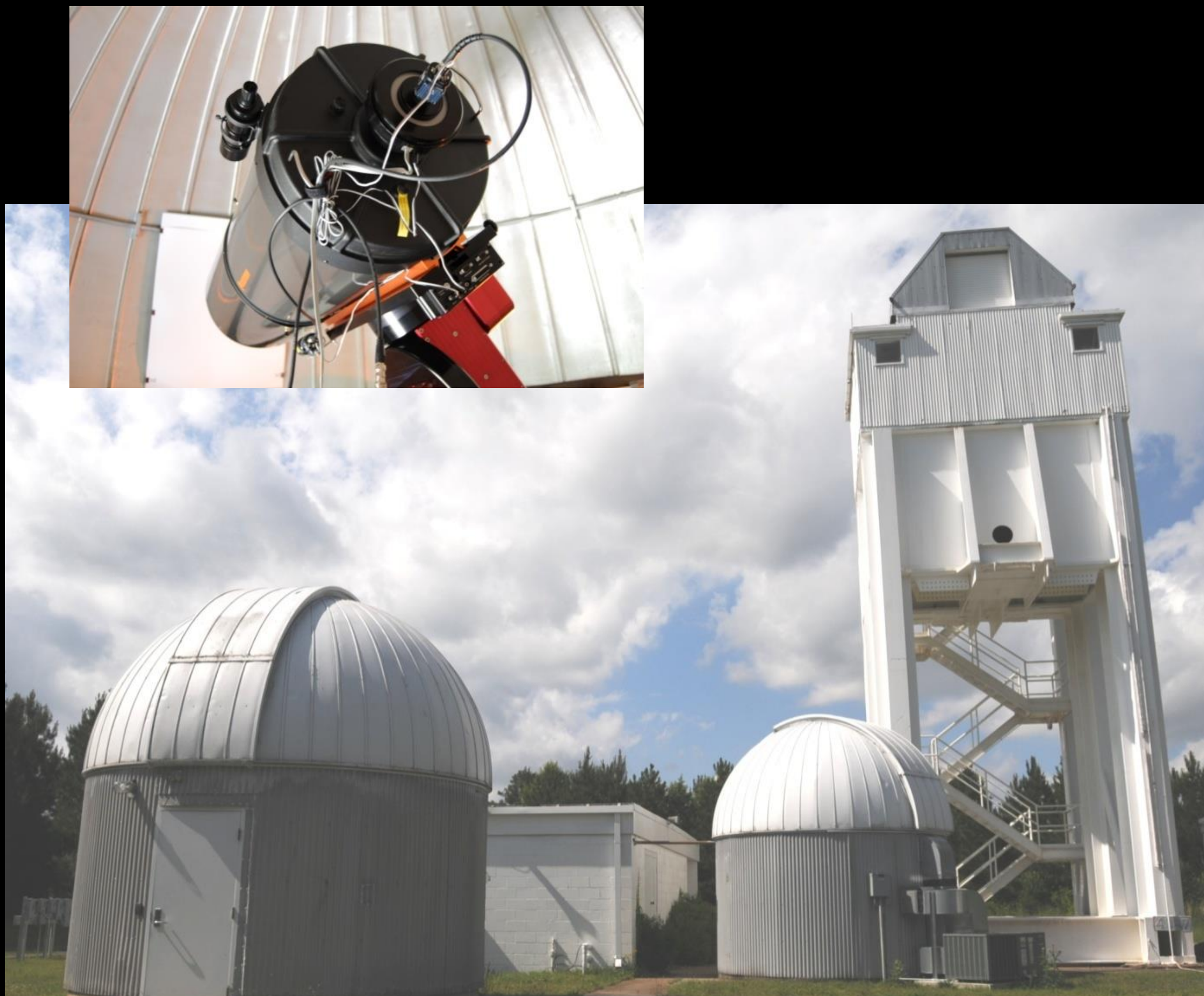
Approximately 1m effective focal length with ½ inch CCD

Good compromise between collecting area and glare

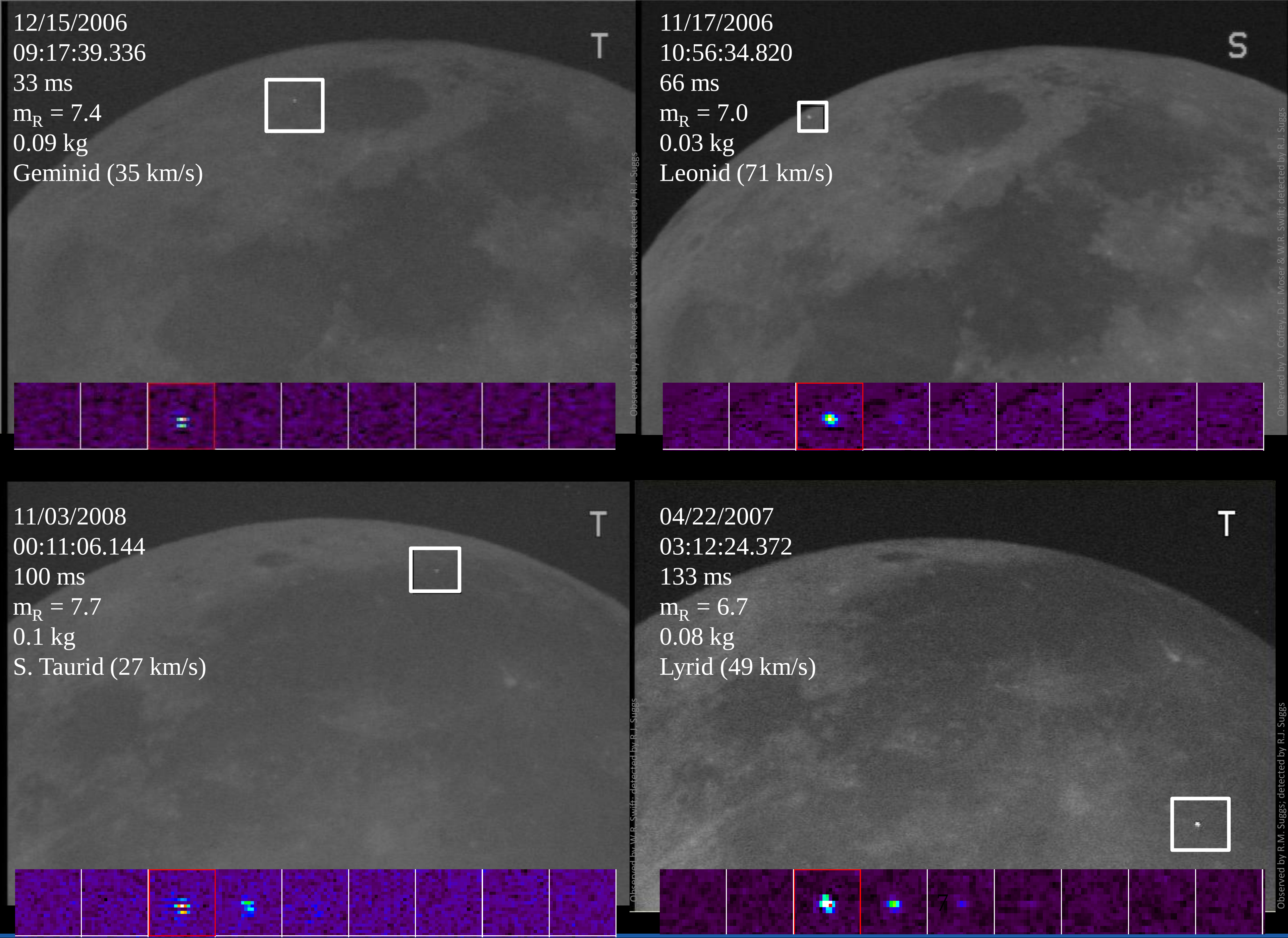
Use stars for photometric calibration

Telescope mount with lunar rate (in RA and Dec) is helpful although manual corrections are needed

Automated Lunar and Meteor Observatory (MPC H58)



- Telescopes
  - 14” (0.35m)
    - Meade, Celestron
  - Paramount (ME, MX)
- Detectors
  - Sony HAD EX – based video
  - Gamma=0.45, man. gain, shutter off


12/15/2006
09:17:39.336
33 ms
m_R = 7.4
0.09 kg
Geminid (35 km/s)
T
11/17/2006
10:56:34.820
66 ms
m_R = 7.0
0.03 kg
Leonid (71 km/s)
S
11/03/2008
00:11:06.144
100 ms
m_R = 7.7
0.1 kg
S. Taurid (27 km/s)
T
04/22/2007
03:12:24.372
133 ms
m_R = 6.7
0.08 kg
Lyrid (49 km/s)
T

Videos

Calibration: Magnitude Equation

Parameters determined by observing stars with known magnitudes

$$R = -2.5\ log_{10}(S) - k'\ X + T\ (B\text{-}V) + ZP$$

R = Johnson-Cousins R magnitude

k' = extinction coefficient

X = airmass (zenith = 1.0)

T = color response correction term

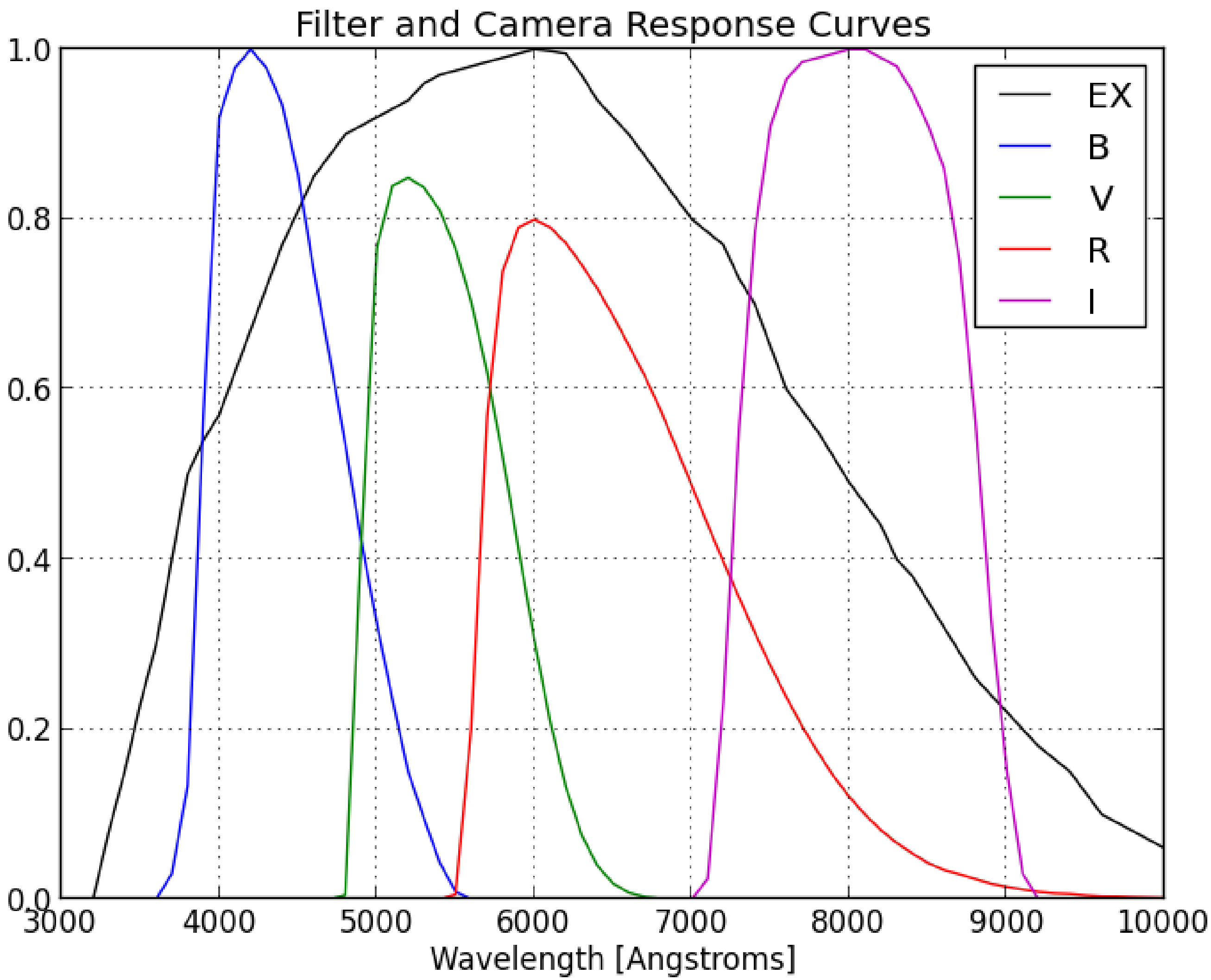
$(B\text{-}V)$ = color index

ZP = zero point for the night

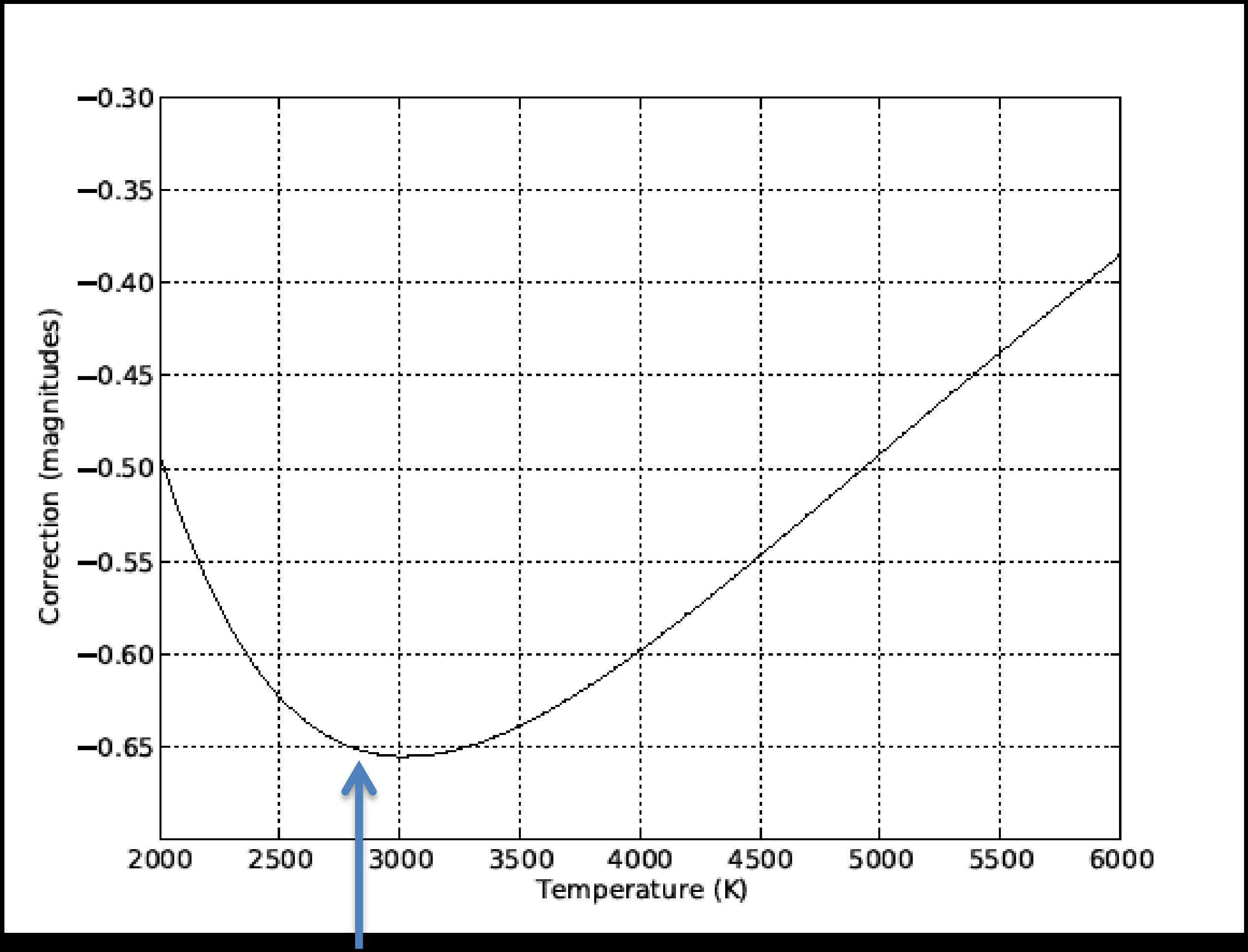
$S = DN^{1/0.45}$ if camera gamma set to 0.45 which extends dynamic range (faintest flash to saturation)

DN = pixel value 0 – 255

Sony HAD EX response compared to Johnson-Cousins filters



Correction from HAD EX to R filter vs blackbody temperature
R-EX replaces T(B-V)



Theoretical peak flash temperature 2800K Nemtchinov et al. (1998)

Luminous energy from impact peak magnitude

$$E_{lum} = f_{\lambda}\, \Delta\lambda \; f \;\; \pi \;\; d^{\,2} \;\; t \qquad \text{Joules}$$

E_{lum} = luminous energy

$\Delta\lambda$ = filter half power width, 1607 Ångstroms for R

f = 2 for flashes near the lunar surface

d = distance from Earth to the Moon

t = exposure time, 0.01667 for a NTSC field

$$f_{\lambda} = 10^{-7}\ \text{x}10^{\,(-R + 21.1 + zp_{R})\,/\,2.5} \qquad \text{J cm}^{-2}\ \text{s}^{-1}\ \text{Å}^{-1}$$

R = the R magnitude

zp_R = 0.555, photometric zero point for *R* (not the same as *ZP* in magnitude equation) from Bessell et al. (1998)

Mass of the impactor assuming impact speed (shower or sporadic)

Luminous efficiency

$$\eta = 1.5\times10^{-3} \exp(-9.3^2/v^2)$$

v = impact speed in km/s

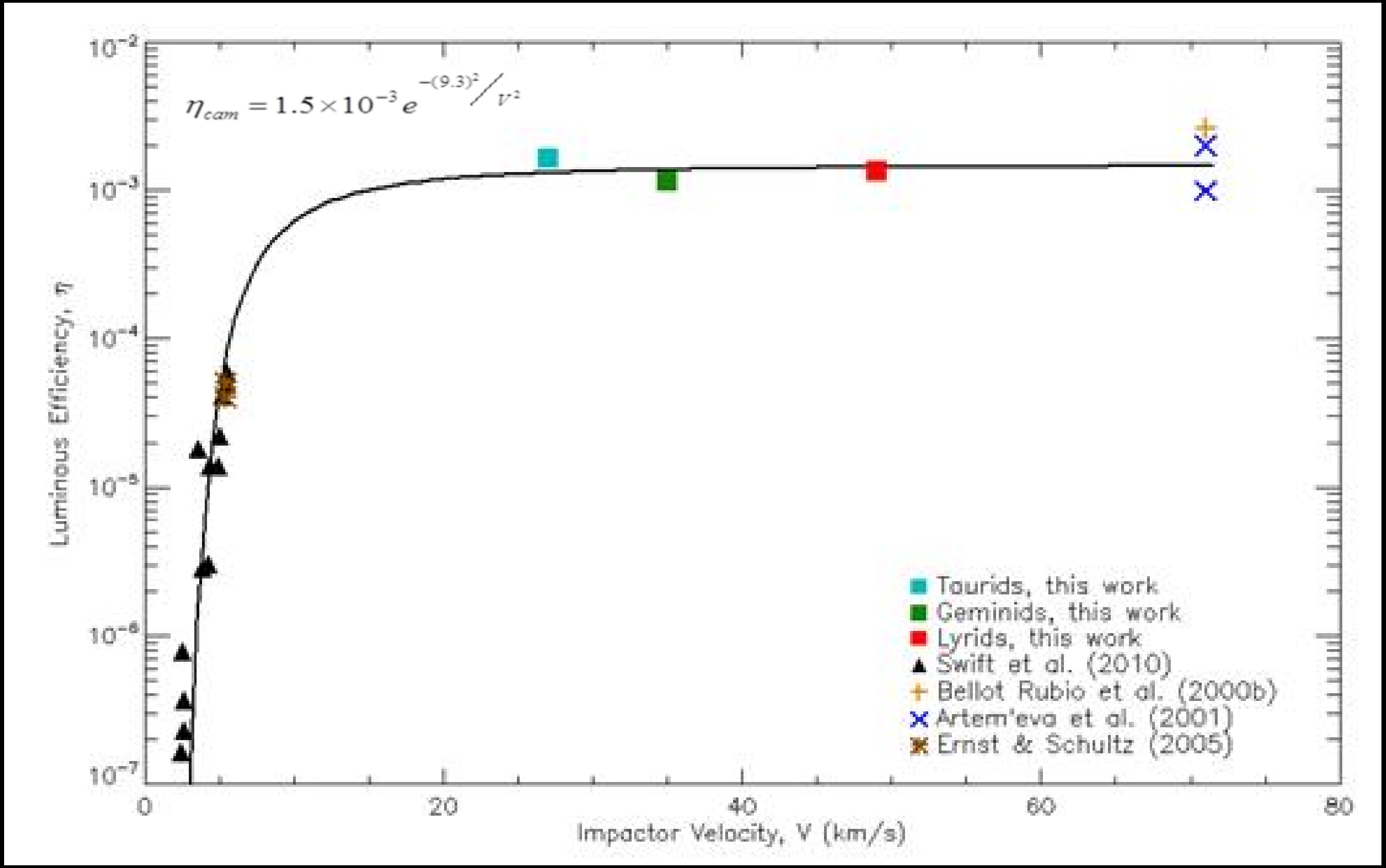
Kinetic Energy

$$KE = E_{lum} / \eta$$

Mass

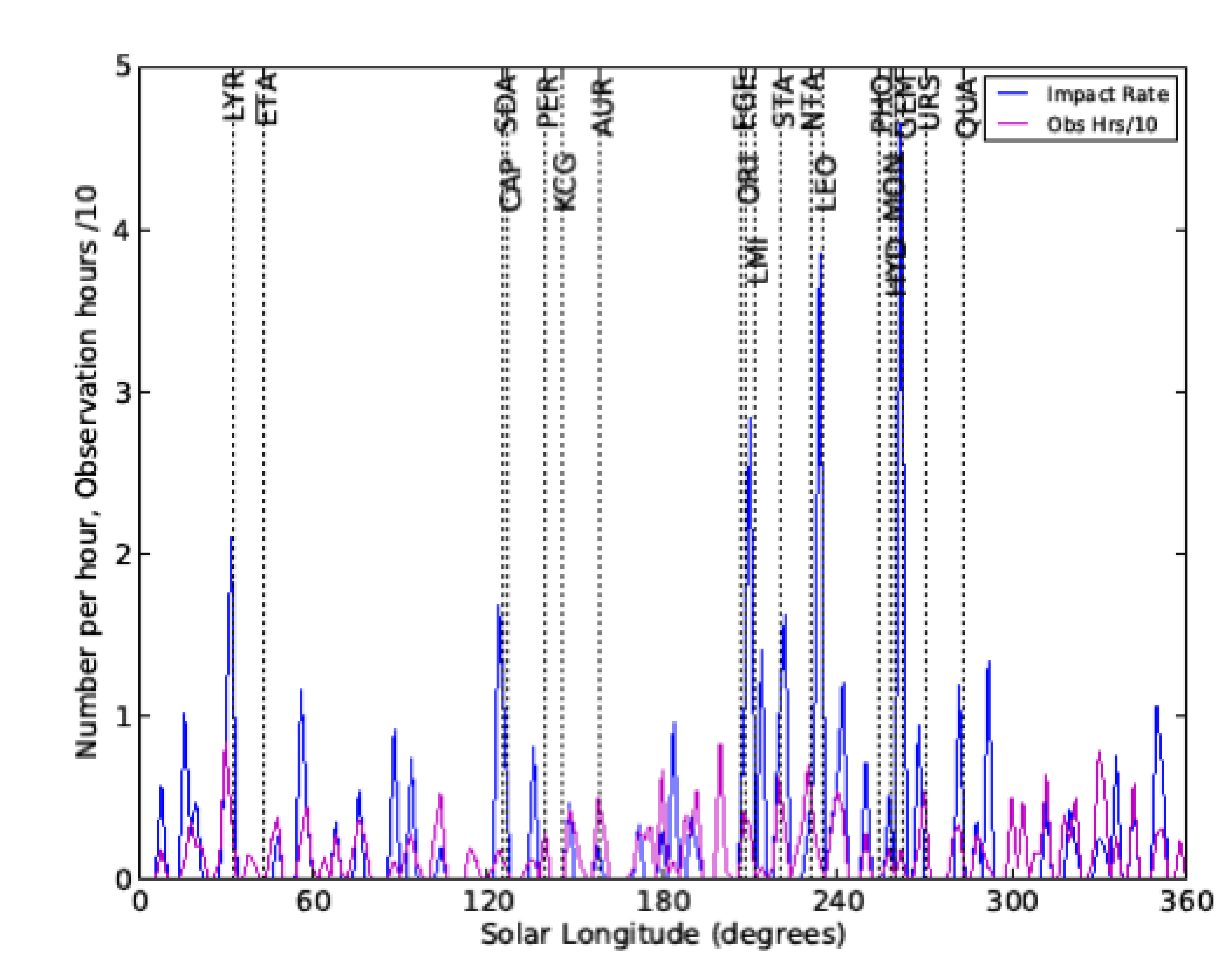
$$M = 2\,KE / v^2$$

Luminous Efficiency

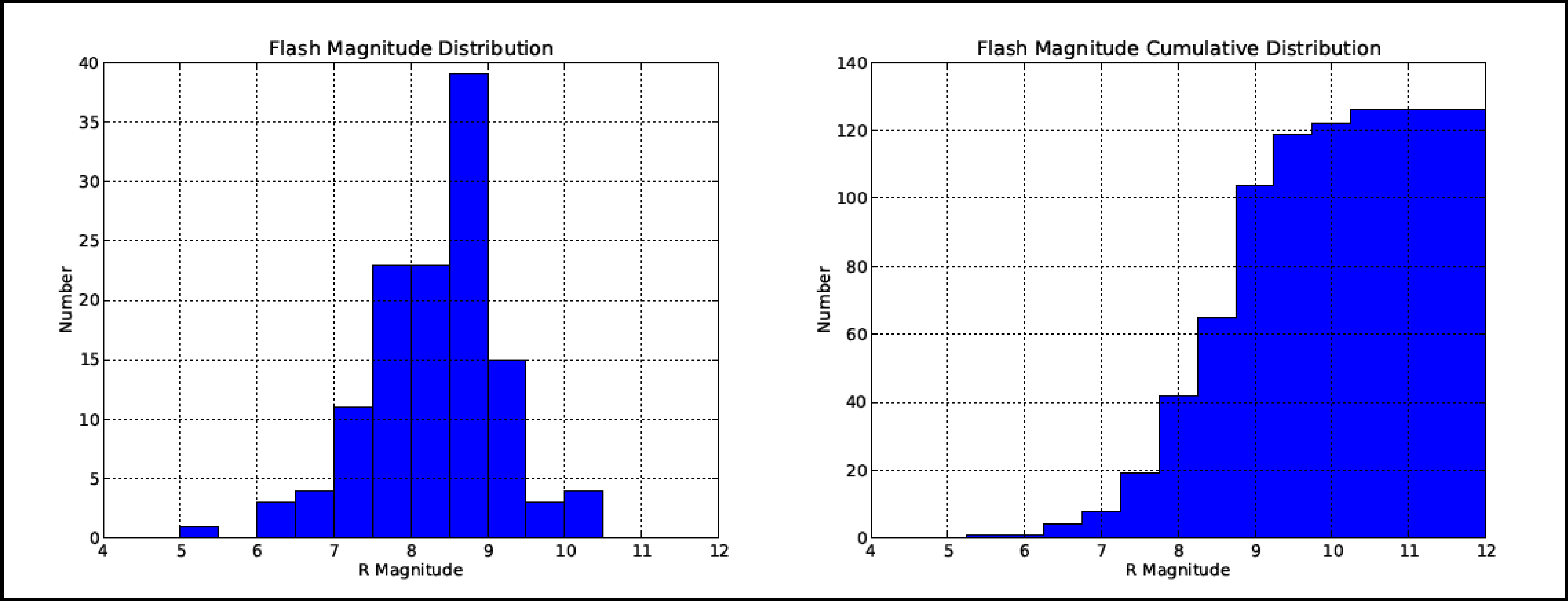


From Moser et al. (2011)

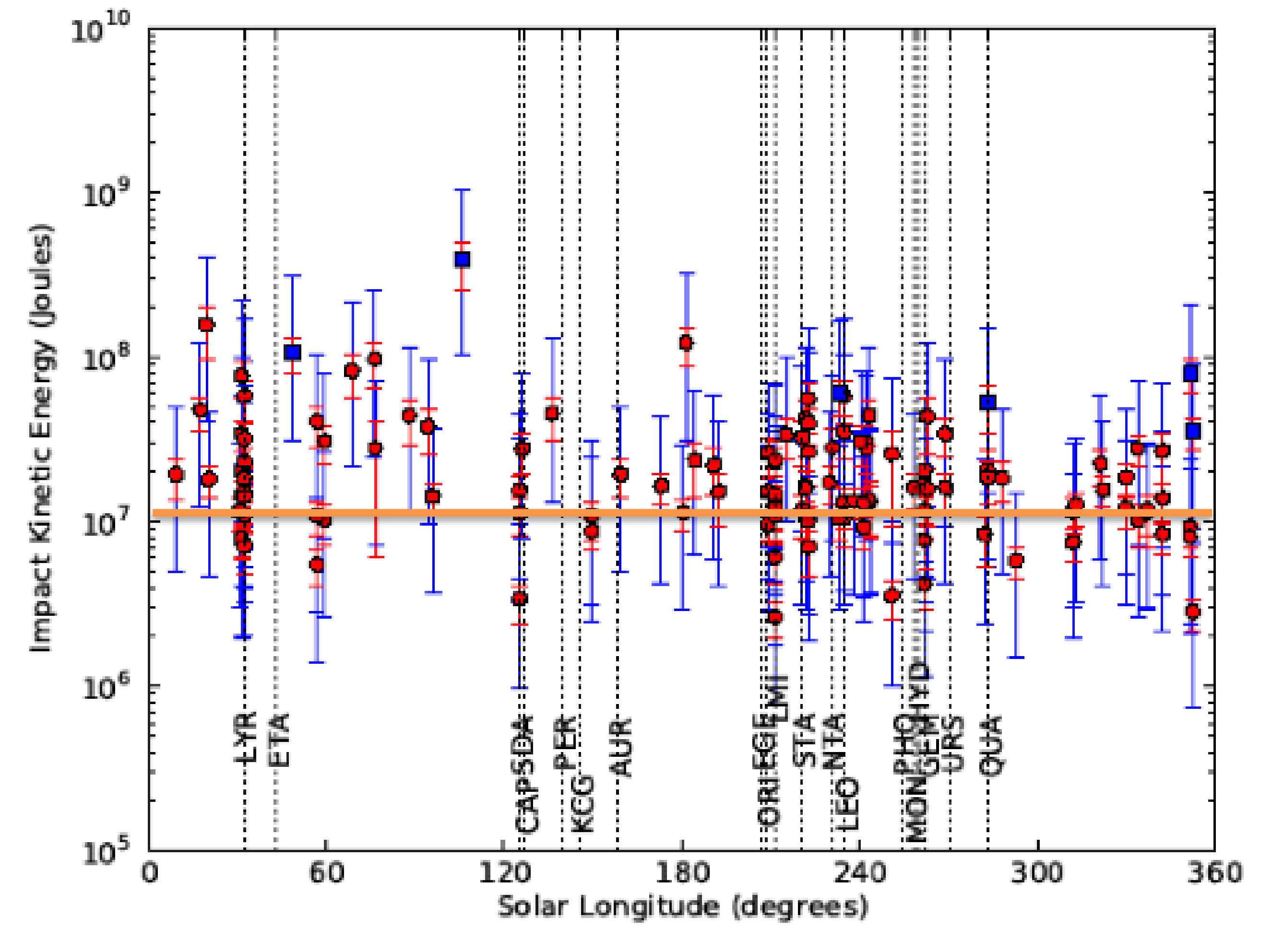
Shower Correlation



Limiting Magnitude



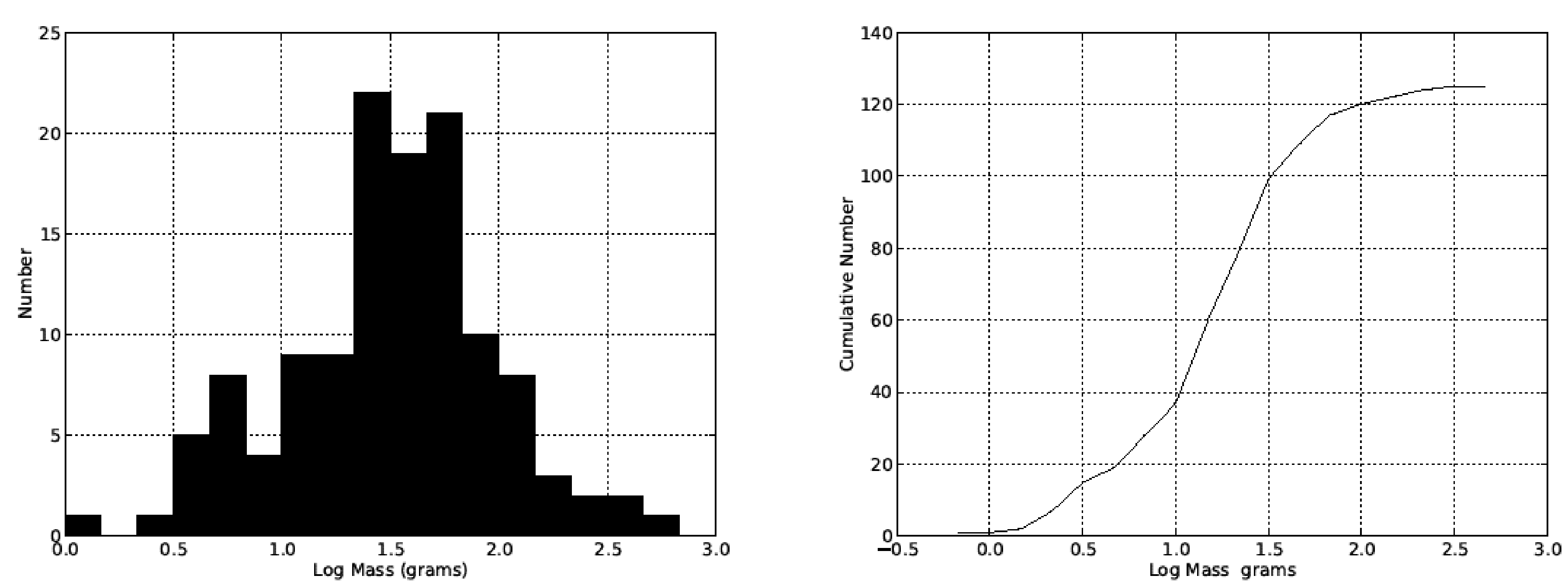
Impact Energies



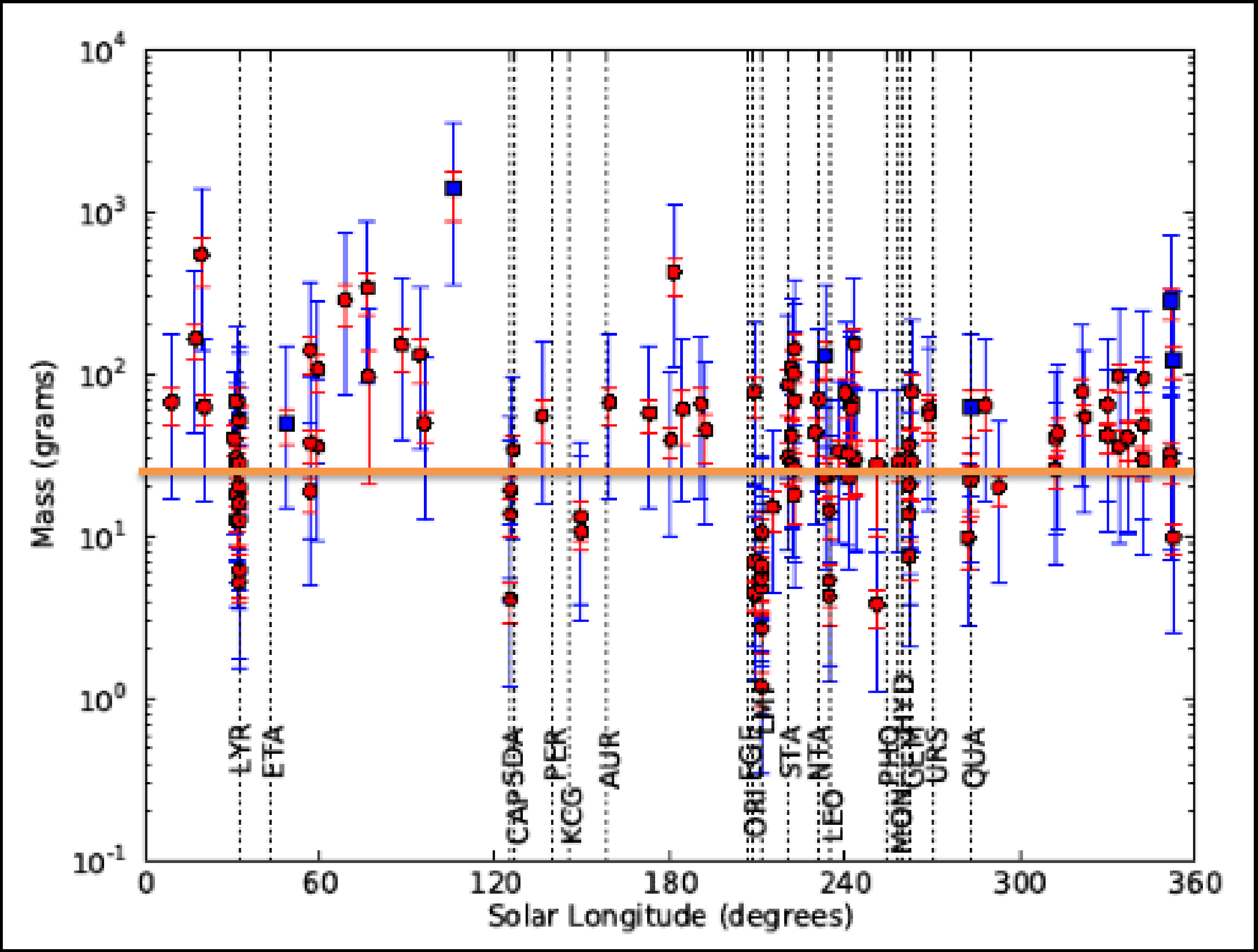
Red error bars - photometric uncertainty; Blue error bars - luminous efficiency uncertainty
Squares indicate saturation

The flux to a limiting energy of 1.05×10^{7} J is 1.03×10^{-7} km^{-2} hr^{-1}

Limiting Mass



Meteoroid Masses



Red error bars - photometric uncertainty; Blue error bars - range of reasonable luminous efficiencies
Squares indicate saturation

The flux to a limiting mass of 30 g is 6.14×10^{-10} m^{-2} yr^{-1}

Comparison with Grün Flux

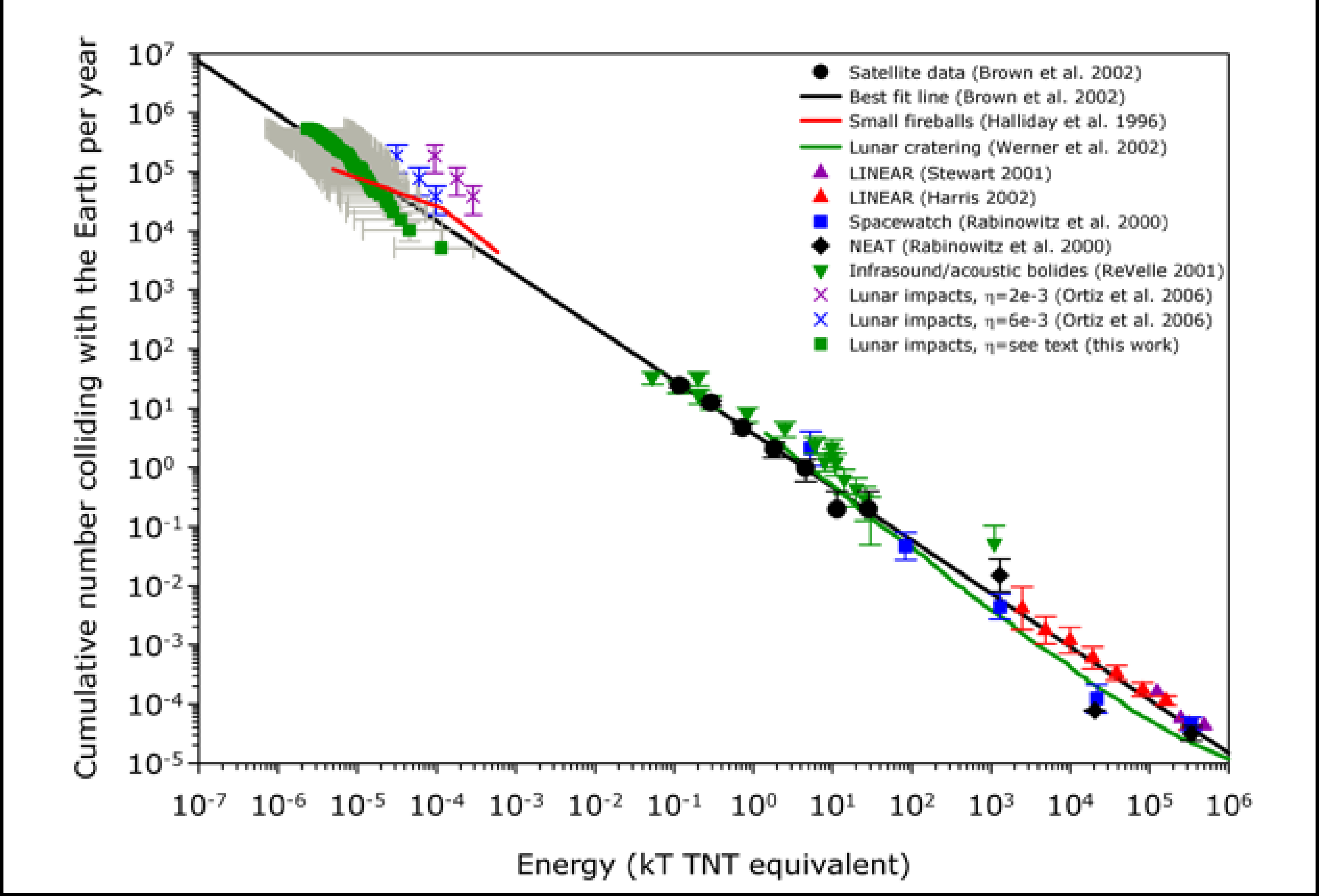
- For our completion limit of 30g we saw 71 impacts for a flux of

  $6.14 \times 10^{-10}\ m^{-2}\ yr^{-1}$

- The Grün et al. (1985) flux above a mass of 30g is

  $7.5 \times 10^{-10}\ m^{-2}\ yr^{-1}$

Impact Flux at Earth Compared with Other Measurements



After Brown et al. (2002)
with adjustments for gravitational focusing and surface area of Earth at 100km altitude

Summary

- We have used a rigorous photometric procedure (observation of standards, color and extinction corrections, etc) to derive flash magnitudes
  - Brightest flashes are saturated; energy/mass under estimated
- Shower membership determined based on radiant visibility from impact location (zenith distance), time from maximum, and peak zhr (Figure of Merit in Suggs et al. 2014) – necessary for mass estimates

  Meteor showers are a significant contributor at cm sizes (>60%) – investigating radiant distribution as possible explanation for observed asymmetry
- Uncertainty in luminous efficiency dwarfs photometric errors – more work needed
- Flux results are consistent with other observational studies

References

Bessell, M.S., Castelli, F., Plez, B., 1998. Model atmospheres broad-band colors, bolometric corrections and temperature calibrations for O-M stars. Astron.m Astrophys. 333, 231-250.

Brown, P.G., Spalding, R., ReVelle, D., Tagliaferri, E., Worden, S., 2002. The flux of small near-Earth objects colliding with the Earth. Nature 420, 294-296.

Grün, E., Zook, H.A., Fechtig, H., Giese, R.H., 1985. Collisional balance of the meteoritic complex, Icarus 62, 244-272.

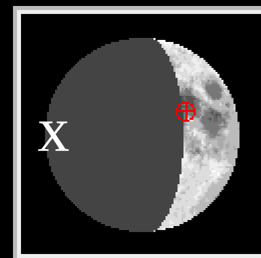
Moser, D.E. , Suggs, R.M., Swift, W.R., Suggs, R.J., Cooke, W.J., Diekmann, A.M., Kohler, H.M., 2011., "Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon Derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids", Meteoroids 2010 Proceedings (NASA CP-2011-216469)

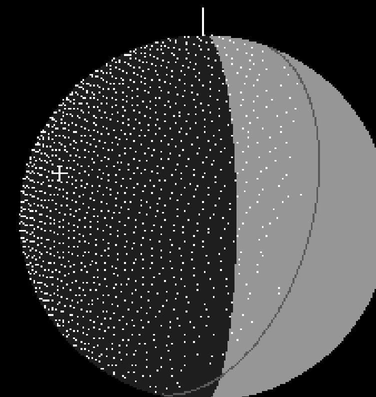
Nemtchinov, I.V., Shuvalov, V.V., Artemieva, N.A., Ivanov, B.A., Kosarev, I.B., Trubetskaya, I.A., 1998. Light impulse created by meteoroids impacting the Moon. Lunar Planet. Sci. XXIX. Abstract 1032.

Suggs, R.M., Moser, D.E., Cooke, W.J., Suggs, R.J., 2014. The flux of kilogram-sized meteoroids from lunar impact monitoring. Icarus 238, 23-36.

Backup

Jack Schmitt/Apollo 17 observation of lunar impact





Geminid visiblity

"NASA Apollo 17 transcript" discussion is given below (before descent to lunar surfac
----
03 15 38 09 (mission elapsed time)
(10 Dec 1972, 21:16:09 UT – possible Geminid)

LMP Hey, I just saw a flash on the lunar surface!

CC Oh, yes?

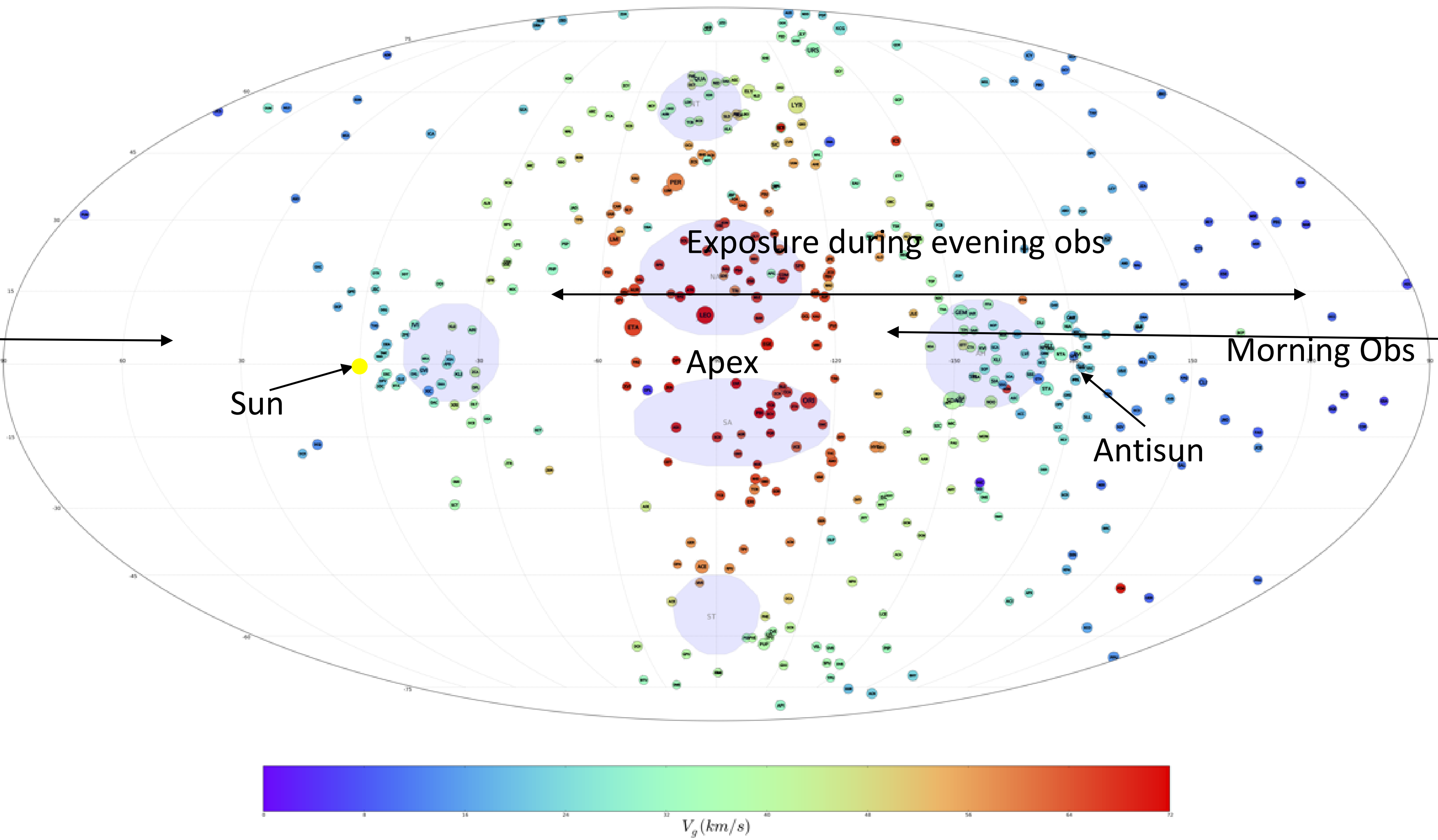
LMP It was just out there north of Grimaldi [mare]. Just north of Grimaldi. You might see if you got anything on your seismometers, although a small impact probably would give a fair amount of visible light.

CC Okay. We'll check.

LMP It was a bright little flash right out there near that crater. See the [sharp rimed] crater right at the [north] edge of [the] Grimaldi [mare]? Then there is another one [i.e., sharp rimed crater] [directly] north of it [about 50km]- fairly sharp one north of it. [That] is where there was just a thin streak [pin prick] [flash?] of light.

CC How about putting an X on the map where you saw it?

Meteor Shower and Sporadic Source Radiants



When We Observe

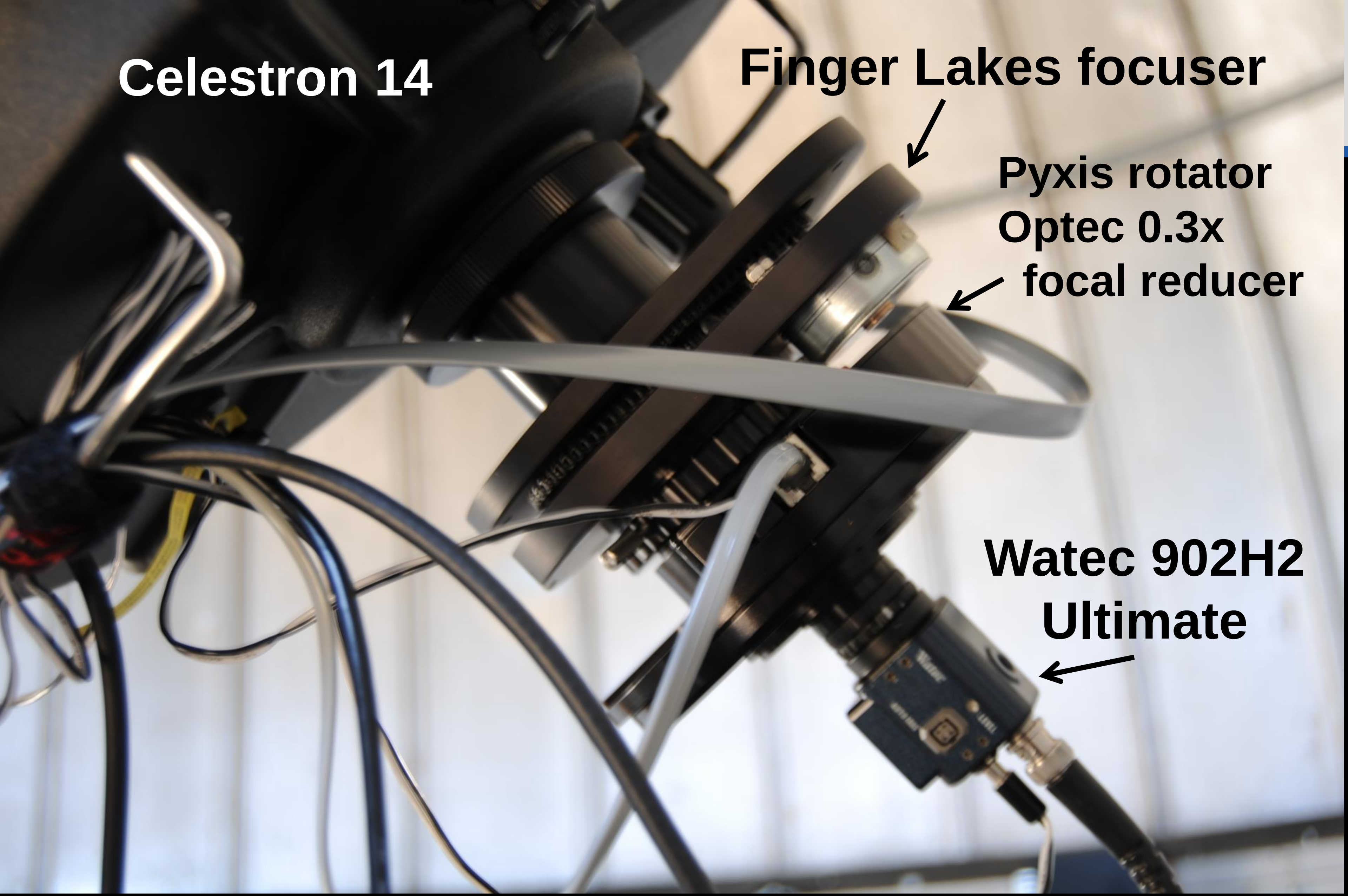
- Initially, it was anytime the glare from the sunlit face did not completely wash out the earthshine face
  - Typically between 10% illuminated (crescent) and 50% (quarter)
- Impact rate is higher during meteor showers and we are focusing on those now after 7 years of observing anytime
- Observe from nautical twilight to moonset – evening
- Observe from moonrise to nautical twilight – morning
- Generate a schedule each year with dates, times, and shower visibilities

Equipment

- Telescopes – 14 inch (0.35m), have also used 0.5m and 0.25m
- Camera – B&W video 1/2inch Sony HAD EX chip (Watec 902H2 Ultimate is the most sensitive we have found)
- Digitizer – preferably delivering Sony CODEC .AVI files if using LunarScan (Sony GV-D800, many Sony digital 8 camcorders, Canopus ADVC-110)
  - This gives 720x480 pixels x8 bits
- Time encoder – GPS (Kiwi or Iota)
  - Initially used WWV on audio channel with reduced accuracy
- Windows PC with ~500Gb fast harddrive (to avoid dropped frames)
  - Firewire card for Sony or Canopus digitizers

Camera Settings

- Manual gain control to do reliable photometry
- Turn off automatic shutter control (ELC on Watec cameras)
- No integration (Sense Up = off for StellaCam or MallinCams)
- Best to use gamma = 0.45 to extend dynamic range at the expense of an extra calculation in the analysis (Gamma Lo for Watecs)


Celestron 14
Finger Lakes focuser
Pyxis rotator
Optec 0.3x
focal reducer
Watec 902H2
Ultimate

Operator position

Photometric Calibration

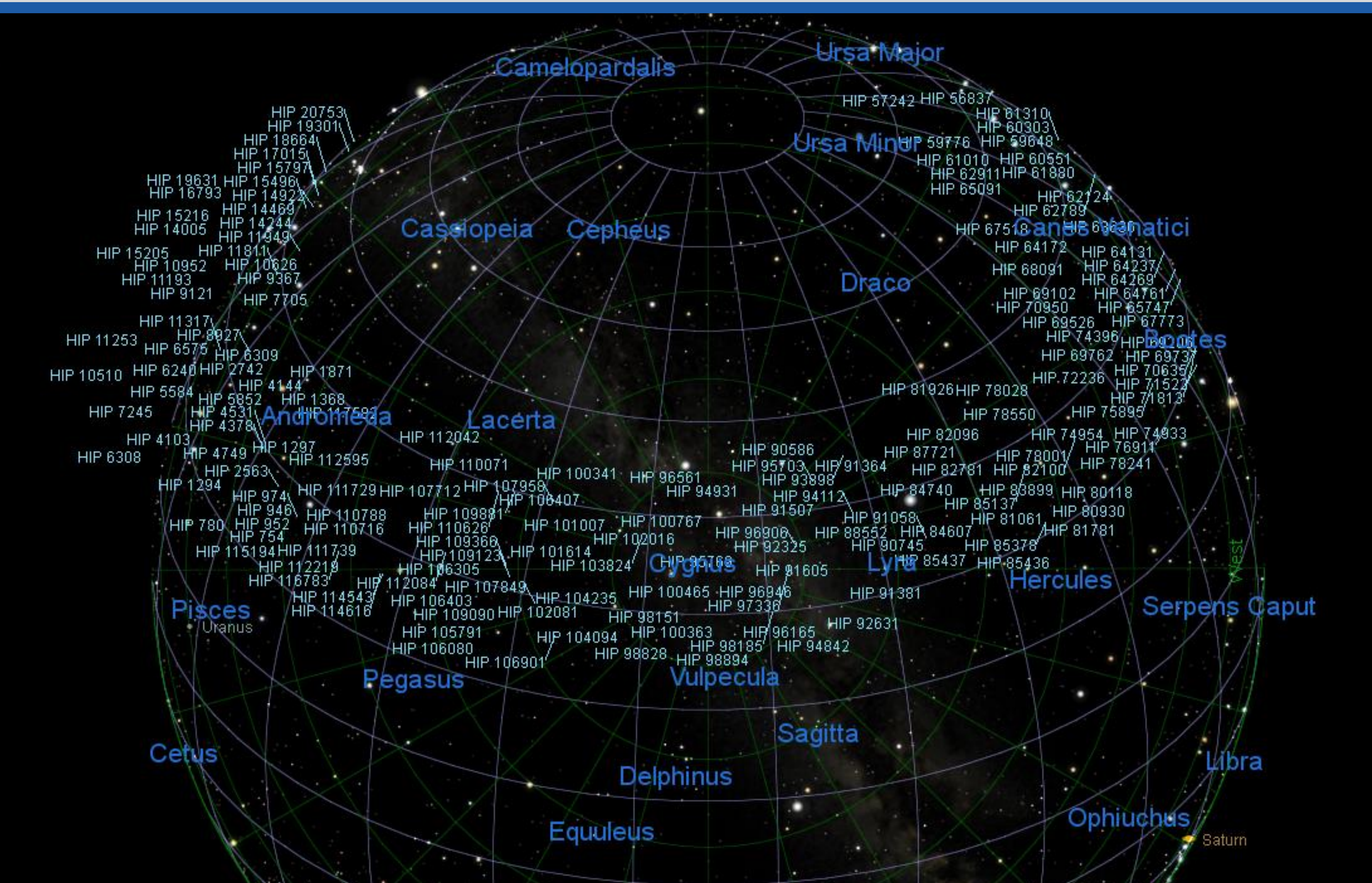
- Use "all sky" photometry
  - Require standard stars with various colors at various airmasses
- Calibration using earthshine is a bad idea
  - Brightness changes with terrestrial weather
  - Color changes with terrestrial weather
  - Extended source vs point source difficulties
- Color correction between filtered magnitude of standards and color of flash is important

Comparison Stars

- Stars will pass through the field of view during observations, but
  - you don't typically know the R magnitude
  - they are seldom in the FOV at the time of the flash
  - this means you **must** do "all sky" photometry rather than "differential" (i.e. must account for extinction as a function of airmass as well as zero point)
  - flat field must be very good because vignetting is worse near the edge of the FOV where the field stars will be seen, especially with focal reduction
- Observe some "standards" at various airmasses (1 and 2 - 3) after evening observations and before morning ones
- Build a standards list using SIMBAD for stars that are bright enough but don't saturate the system (8 – 9 R mag for 14in) that pass through the zenith simbad.u-strasbg.fr/simbad/
  - Must have published R and B-V mag and not be a variable or multiple

$$R = -2.5 \log(S) - k' X + T\,(B\text{-}V) + ZP$$

Comparison Stars



Filters and Photometric Calibration

- Use the camera unfiltered to give maximum sensitivity
  - Wider spectral response
    - near infrared where the flash is brightest
    - blue and green where earthshine is brightest (to see features)
- Calibration should be done with R magnitudes of comparison stars
  - Peak sensitivity of HAD EX and R filter is at the same wavelength but width is very different
  - Need the color term T (B-V) = EX-R in the magnitude equation

$$R = -2.5 \log(S) - k' X + T\,(B\text{-}V) + ZP$$

Software we have used

- WinDV for recording windv.mourek.cz
- LunarScan detection software (Gural will discuss) www.lunarimpacts.com/lunarimpacts.htm
- VirtualDub for slicing out relevant sections of video and converting to "Old AVI" for reading into Limovie www.virtualdub.org/download.html
- Limovie for checking photometry of flashes and calibration stars www005.upp.so-net.ne.jp/k_miyash/occ02/limovie_en.html
- MaximDL can convert video segments to FITS
  - Don't use the aperture photometry tool until after each pixel is gamma corrected by $S = DN^{1/0.45}$ if camera gamma set to 0.45
- Python and Pyraf may be used for aperture photometry www.stsci.edu/institute/software_hardware/pyraf/current/download

Important Points

- Flux determination requires a measurement of the number of hours of observation to a particular limiting magnitude
  - Do not count cloudy hours
  - Cumulative peak magnitude diagram is useful in determining limiting magnitude
- We use peak magnitude rather than a time integrated magnitude
  - Later phases of an impact "light curve" are dominated by cooling of the ejecta and crater – relation to impact energy is contaminated by regolith properties
  - How long the flash is visible depends on variables such as atmospheric transparency and earthshine

Filter and camera responses depend on color of object