Quasars, Pulsars, Gamma-Ray Bursts! Oh, my!

Collapsars, magnetars, X-ray pulsars, γ-ray pulsars, millisecond radio pulsars…

Giacconi et al. (1962)

- Rocket carried 3 Geiger counters to 225km - one counter failed (#1).
- Windows of counters pointed 55° from the axis of the rocket (i.e. the Zenith).
- Windows made of mica covered with lampblack.
- Rocket rotated at 2.0 rps, 350 s above 80km.

The Data

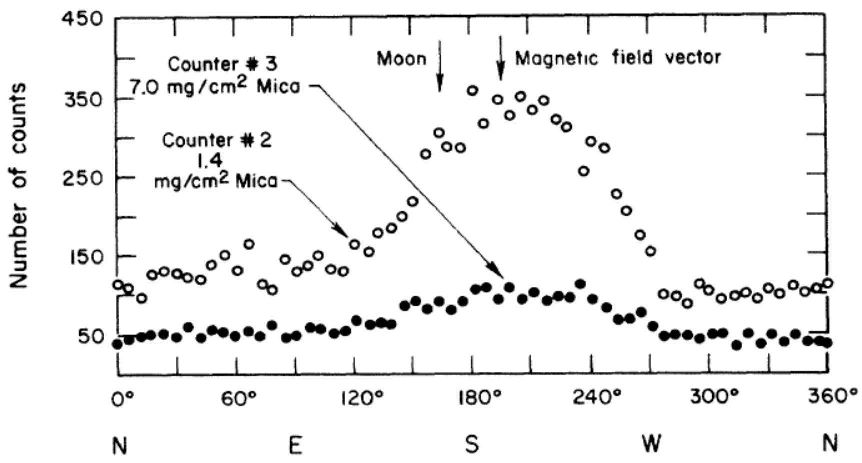
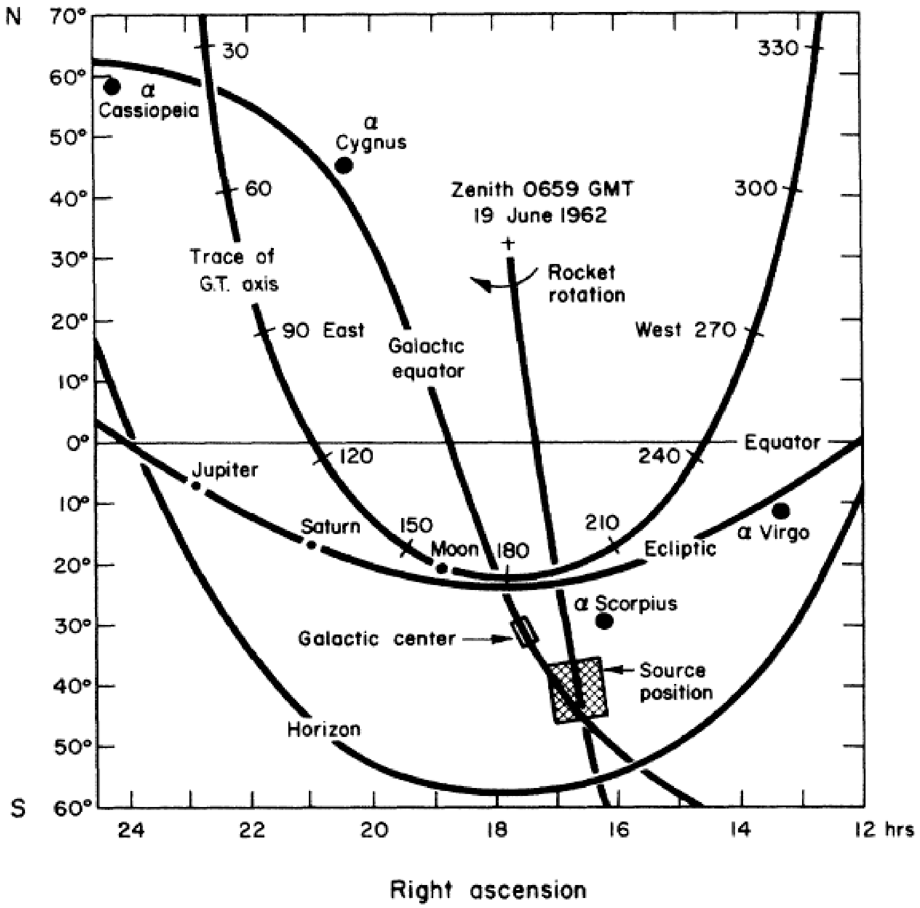


FIG. 1. Number of counts versus azimuth angle. The numbers represent counts accumulated in 350 seconds in each 6° angular interval.

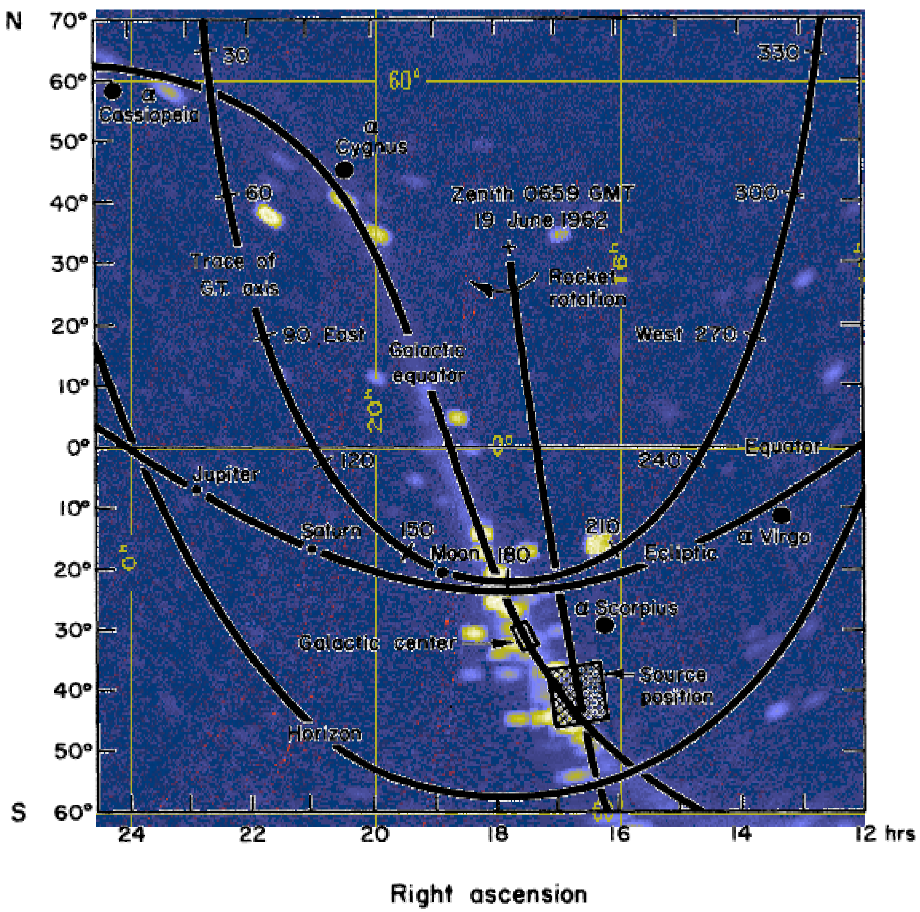


The Results

- They argued that the source was located about 10° above the horizon by comparing the absorption through the air and the mica assuming monochromatic source.

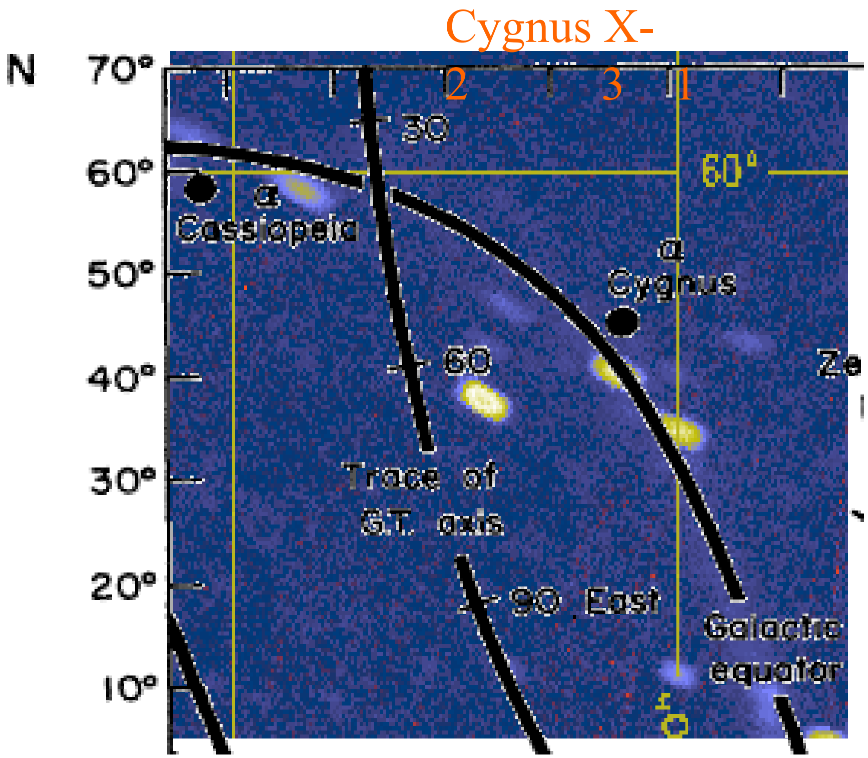
What Did the Aerobee See?

- Fig. 2 superimposed on the HEAO all-sky survey.
- The object known as Sco X-1 is the brightest in the X-ray sky at an azimuth angle of 210° along the G.T. axis.



What about the scruff at 60°?

- The detection at 60° albeit not as dramatic as the 210° result is also associated with an LMXB, Cygnus X-2.
- What is the flux of Cygnus X-2 compared with Sco X-1?



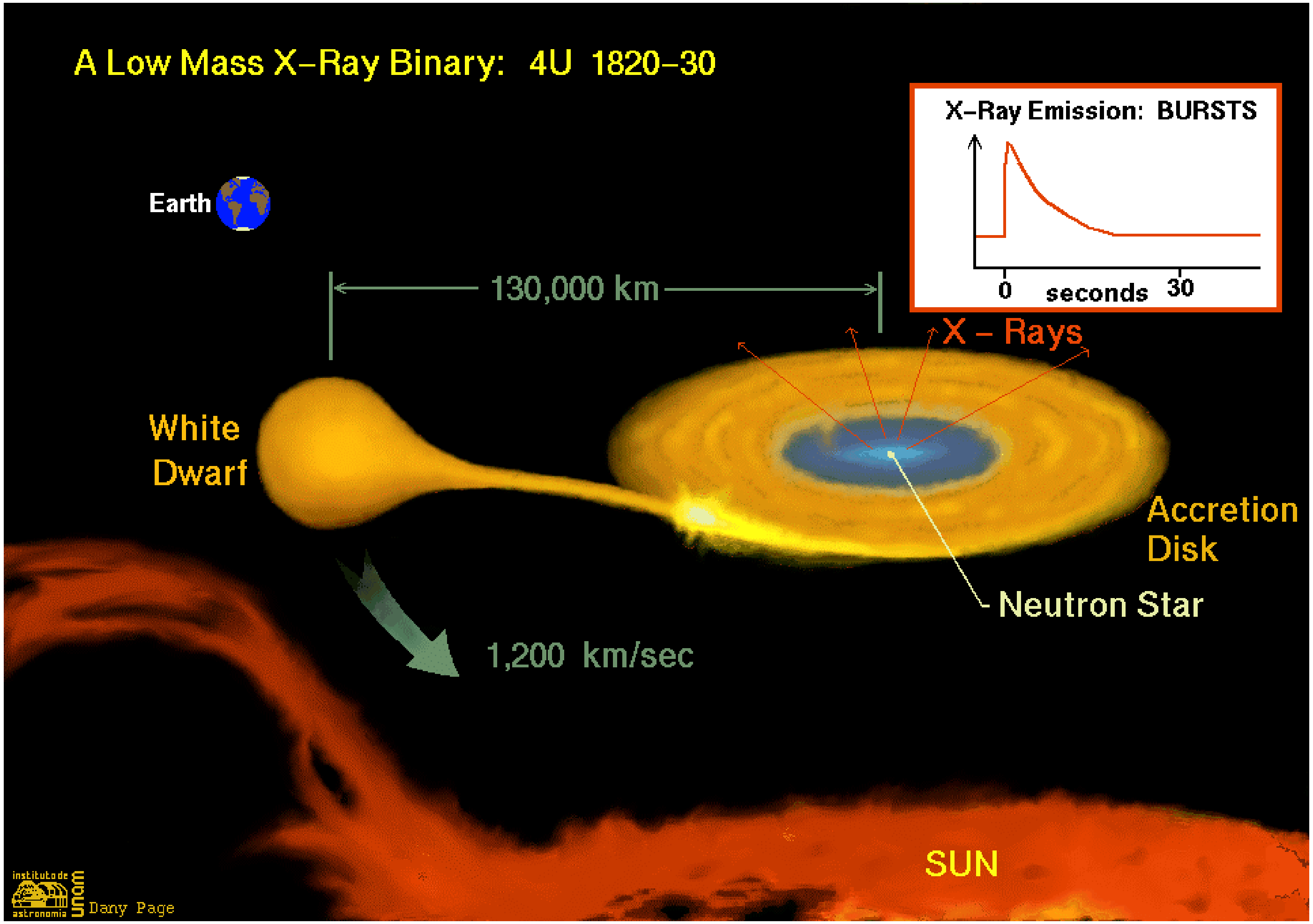
The Answer:

- Sco X-1: 14000 μJy (LMXB)
- Cyg X-1: 235-1320 μJy (HMXB)
- Cyg X-2: 450 μJy (LMXB)
- Cyg X-1: 90-430 μJy (HMXB)
- BTW:
  - What were they looking for from the moon?
  - What became of American Science and Engineering?

LMXBs and HMXBs

- Low-mass X-ray Binaries
  - Low mass main sequence star or white dwarf in orbit with a neutron star or black hole
  - Roche lobe overflow driven by gravitational radiation
- High-mass X-ray Binaries
  - High mass main sequence star in orbit with a neutron star or black hole
  - Wind accretor or Roche lobe overflow

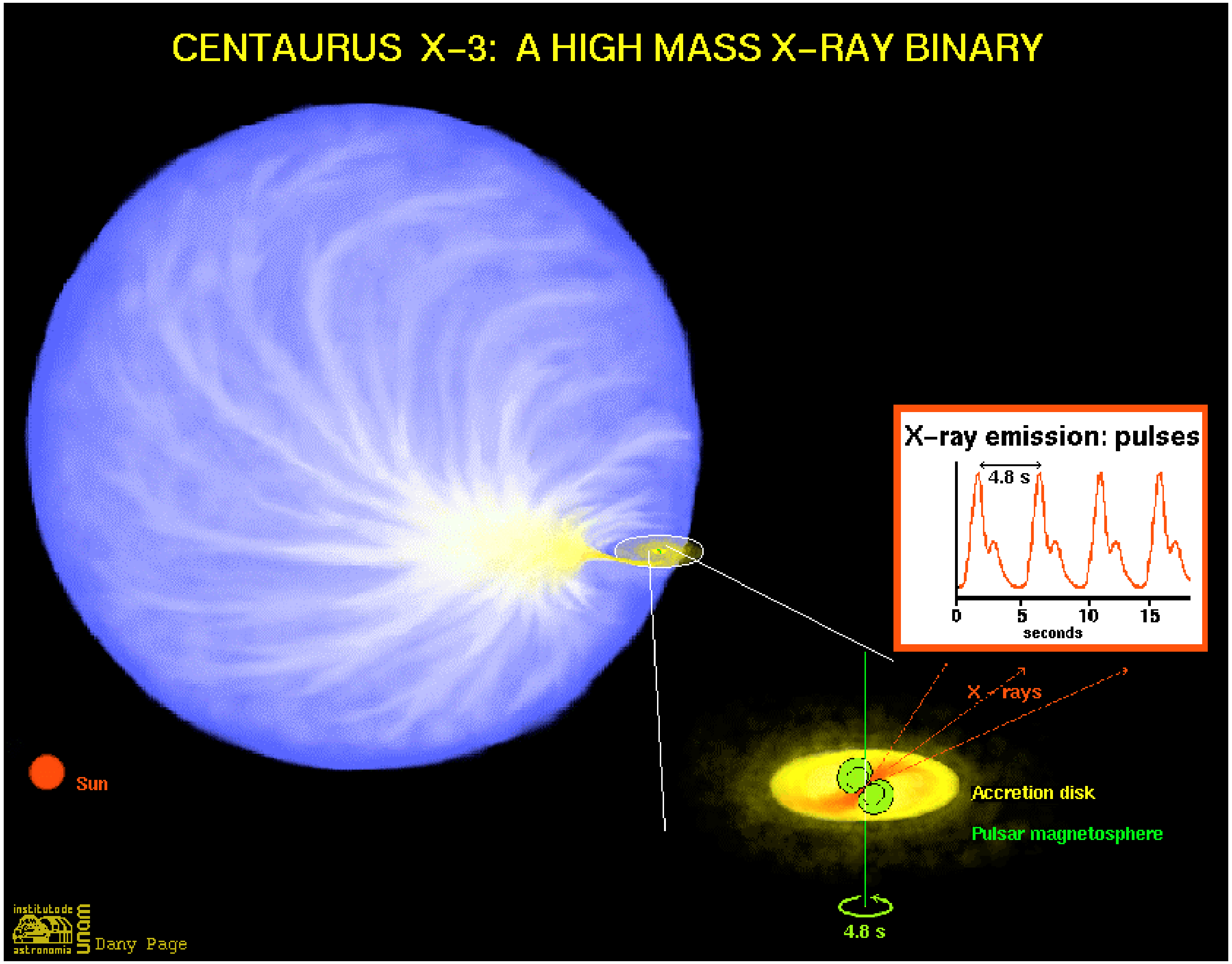
LMXBs


A Low Mass X-Ray Binary: 4U 1820-30
X-Ray Emission: BURSTS
0
seconds
30
Earth
130,000 km
X – Rays
White Dwarf
Accretion Disk
Neutron Star
1,200 km/sec
SUN
instituto de astronomía unam
Dany Page

LMXB Properties

- Long-lasting system - GR drives the evolution
- NS/BH can accrete much of the donor’s mass
  - The donor might be disrupted completely.
  - The neutron star gains lots of angular momentum.
  - Magnetic field of the neutron star gets “buried.”
- The faint donor is tidally distorted.
  - Orbit is circularized and tidally locked.
  - Accretion rate does not depend on orbital phase.
  - It is hard to see the changing aspect of the donor in the glare of the accretion disk.
- Result: MSP with WD or alone.

HMXBs



CENTAURUS X-3: A HIGH MASS X-RAY BINARY
X-ray emission: pulses
4.8 s
0
5
10
15
seconds
X - rays
Sun
Accretion disk
Pulsar magnetosphere
4.8 s
Dany Page

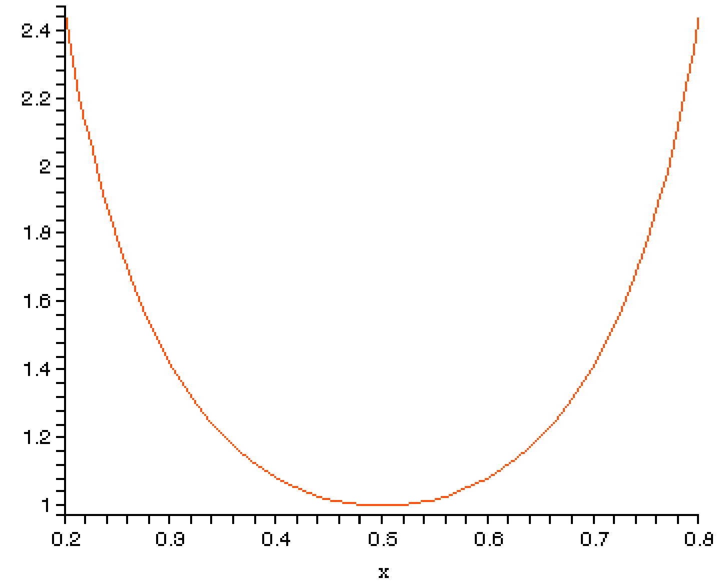
HMXB Properties

- Short-lived system - stellar evolution
- NS/BH accretes little of the donor's mass
  - The donor may evolve normally.
  - Magnetic field of the neutron star preserved.
- The bright donor may only be minimally distorted.
  - Orbit may be elliptical.
  - Accretion rate may depend on orbital phase.
- Result: BH/NS with BH/NS/WD or alone.

Binary Stellar Evolution

- When mass moves from one star to the other, the orbit changes. Need to remember Kepler's Laws!
  - Second Law: $\Omega\, a^2\, M_1 M_2/(M_1+M_2) = L$
  - Third Law: $\Omega^2 a^3 = G\,(M_1+M_2)$
  - 2nd + 3rd:

$$a = \frac{L^2 M}{G M_1^2 M_2^2}$$



LMXBs and HMXBs

- In an LMXB, the donor is **less** massive than the neutron star, so the orbit will widen ending the mass transfer, unless L is not conserved or the donor expands as it loses mass.
- In an HMXB, the donor is **more** massive than the neutron star, so the orbit will shrink increasing the mass transfer.

Roche Lobe

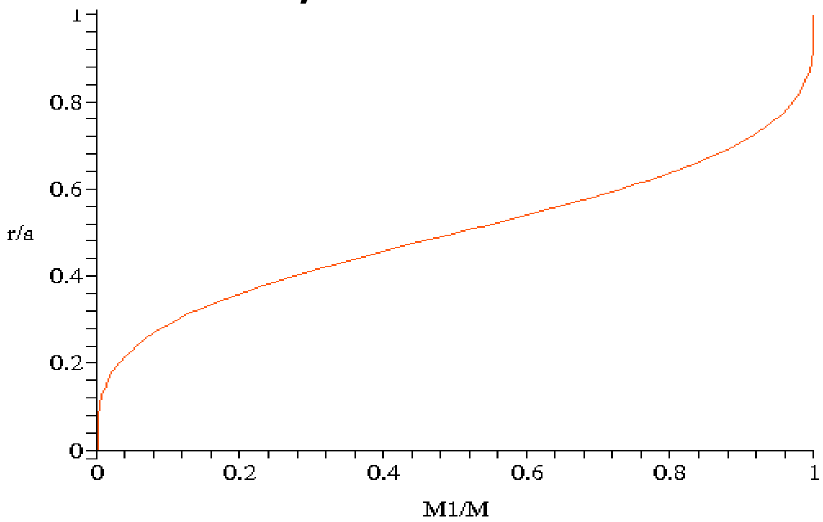
- The force pulling a particle toward the centre of the star equals the force pulling it away.

$$\frac{F}{m} = -\frac{GM_1}{r^2} + \frac{GM_2}{(a-r)^2} - \Omega^2\left(a\frac{M_2}{M} - r\right)$$

- With some algebra you find that,

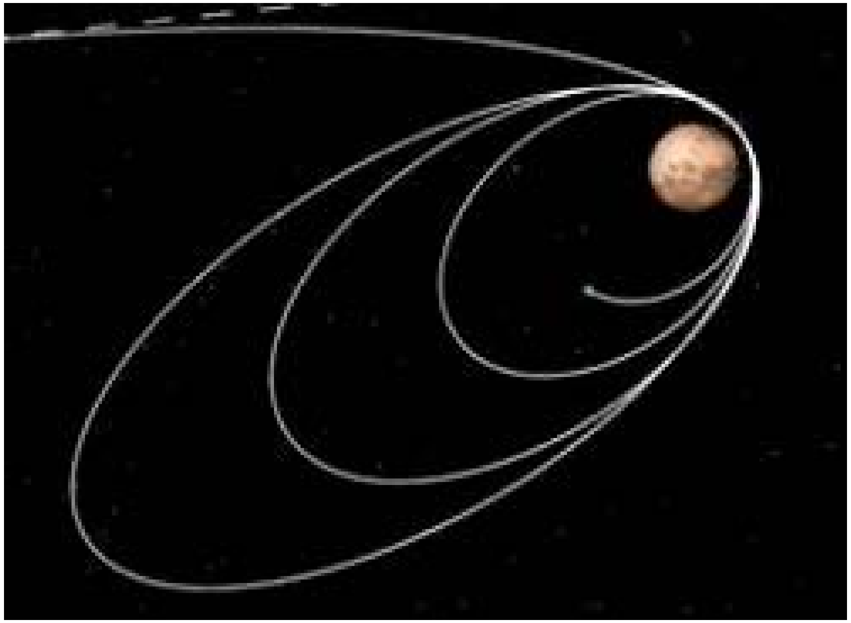
$$\frac{F}{m} = \frac{GM}{a^2} f\left(\frac{r}{a}, \frac{M_1}{M}\right)$$

where f = **UGLY**.



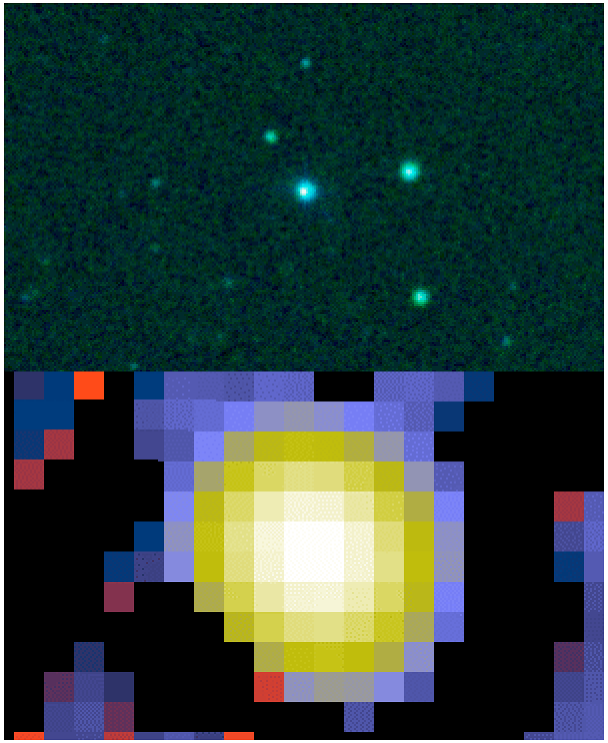
Tidal Circularization

- A topical analogy to understand how this works is aerobraking.
- Raising the tides dissipates orbital energy as friction in the star.
- Because the energy is removed at periastron, the apastron moves inward.



Quasars - Active Galaxies

- The nuclear activity of galaxies spans a wide spectrum ranging from normal galaxies through Seyfert galaxies and radio galaxies to quasars and QSOs.
- QSO - quasi-stellar object
- Quasar - quasi-stellar radio source
- The term QSO has fallen out of use.
- The key surprise about 3C 273 and 3C 48 was of course their distance.
- Luminosity of about 10^{47} erg/s from a small region -- you'll estimate their masses in the problem set.



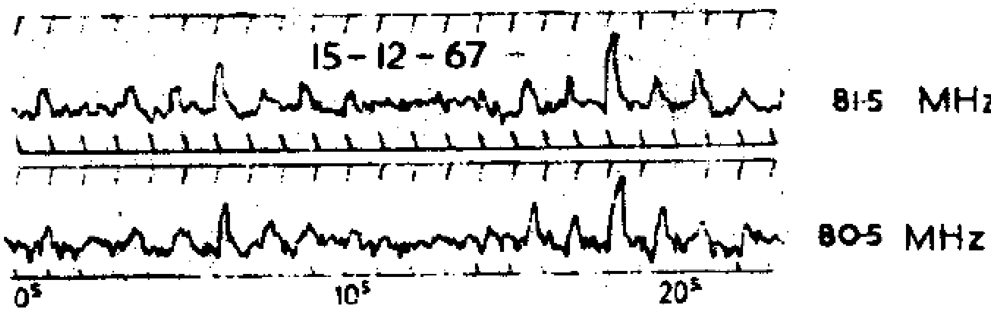
3C 273 in B/R/J (DSS/2MASS) and at 1.4 GHz (VLA NVSS)

Hewish et al. (1968)

- Built a large multibeam antenna to look at scintillation of quasar radiation through the interplanetary plasma.
  - Sensitive
  - High time resolution
  - Low frequency

What did they observe?

- "Bits of scruff that appeared at the same sidereal time each day"
- The pulses arrive slightly later at lower frequencies.
- Used the expected frequency drift due to the Earth's motion to determine the position of the source on the sky.
- The position did not change over the year.



- The pulse frequency is constant except for the Earth's Doppler shift.
- Suggested that it was pulsation of a white dwarf or neutron star.

Light through Plasmas

- A plasma is a fluid in which the charged particles are free to move (there are currents).

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \qquad \nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$$

- Taking the time derivative of (1) and putting into the curl of (2),

$$\nabla \times (\nabla \times \mathbf{E}) + \frac{4\pi}{c^2}\frac{\partial \mathbf{J}}{\partial t} + \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = 0$$

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E}$$

- Let’s assume that no net charge develops so the first term vanishes.

Now the currents

- A current is a charge times a velocity,

$$\mathbf{J} = n_e e \mathbf{v} \;\; \text{and} \;\; \dot{\mathbf{J}} = n_e e \dot{\mathbf{v}}, m_e \dot{\mathbf{v}} = e\mathbf{E}$$

where we have assumed that v<<c.

- Combining the last few equations gives,

$$-\nabla^2 \mathbf{E} + \frac{4\pi n_e e^2}{c^2 \; m_e}\mathbf{E} + \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = 0$$

- Let $\mathbf{E} = \mathbf{E}_0 e^{i(kx - \omega t)}$ and substitute

$$k^2 \mathbf{E} + \frac{\omega_p^2}{c^2}\mathbf{E} - \omega^2 \mathbf{E} = 0 \;\; \text{with} \;\; \omega_p^2 = \frac{4\pi n_e e^2}{m_e}$$

Dispersion Measure (1)

- EM radiation travelling through a plasma has the dispersion relation:

$$\omega^2 = \omega_p^2 + c^2 k^2 \ \text{ so } \ v_g = \frac{d\omega}{dk} = c^2 \frac{k}{\omega} = c\sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

- So, the pulse travels faster at higher frequencies,

$$t = \frac{L}{v_g} \ \text{ so } \ \frac{dt}{d\nu} = \frac{L}{c} \frac{\nu_p^2}{\nu^3 \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{3/2}}$$

Dispersion Measure (2)

- We can also use a integrated quantity,

$$t_2 - t_1 = \frac{2\pi e^2}{mc}(\omega_2^{-2} - \omega_1^{-2}) \int_0^d n_e dl$$

- The dispersion constant is

$$D = (t_2 - t_1)/(\nu_2^{-2} - \nu_1^{-2})$$

and the dispersion measure is

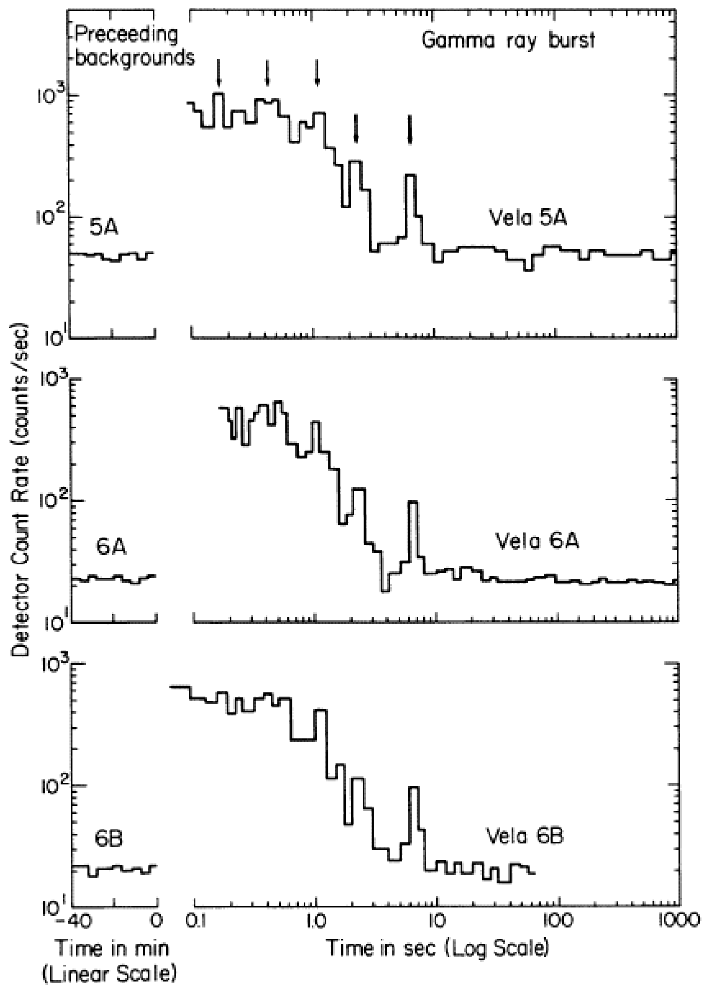
$$DM \ \ (\mathrm{cm^{-3}pc}) = 2.410 \times 10^{-16} D \ \ (\mathrm{Hz})$$

Why is it important?

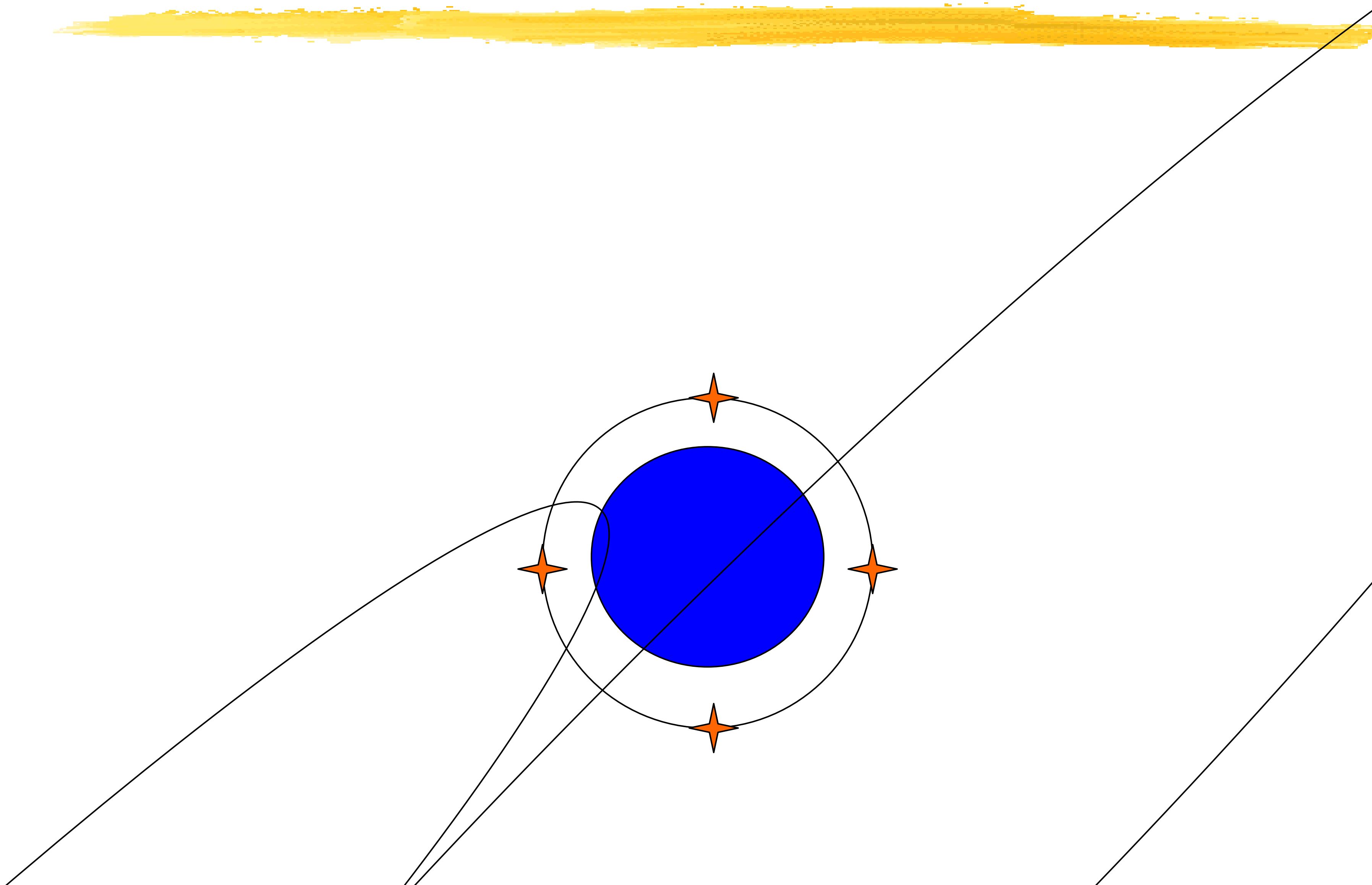
- The paper has outlined many of the techniques used in pulsar astronomy today:
  - DM distances
  - Pulse counting
  - Doppler positioning
  - The name "pulsar" for pulsating star (this ended up being the wrong model)
- How did they do it?
- The key was that they were looking for scintillation, so they
  - Looked at low frequencies where pulsars are brightest.
  - Used a fast time constant, multiple frequencies and lag cables to see the time shifts induced by scintillation.
  - Sensitivity - pulsars on average aren't that bright.

Klebesadel et al.

- Four Vela satellites in Earth orbit observed several bursts of gamma-rays.
- Could use timing of the burst arrival to determine the location on the sky and extra-terrestrial origin.



Locating GRBs



Fast Forward