todays lecture

- Line of sight effects
- Effect of magnetic field on accretion
- How to derive the mass of the compact object
- Accretion disk (start)

Ahumada Mena,	Tomas
Carvajal, Vivian	**Frances**
Crnogorcevic,	Milena
DeMartini,	Joseph
Dittmann,	**Alexander**
Fu,	**Guangwei**
Grell,	**Gabriel**
Hammerstein,	Erica
Hinkle,	**Jason**
Hord,	**Benjamin**
Ih,	**Jegug**
Karim,	Ramsey
Koester,	**Kenneth**
Marohnic,	Julian
Mundo	**Santiago,**
Park,	**Jongwon**
Teal, '	
Thackeray,	**Yvette**
Villanueva	Vicente
Volpert,	**Carrie**
Ward,	Charlotte
Williams,	Jonathan
Yin,	**Zhiyu**

Oral Presentations

14 students have not presented yet...after today we have only 9 lectures; the math is obvious

If no one volunteers I will assign talks in reverse alphabetical order; e.g Zhiyu would be next, then Carrie, Yvette etc. Aiming for 2 per lecture.
This will start April 16 and then
April 18,April 23, April 30, May 2, May 7 and May 9 and the 'last class'

I will consider changing this if the next person in line agrees.

Red has given talk

Papers Open for Selection Today

Next Paper(s) •Modelling the behaviour of accretion flows in X-ray binaries Everything you always wanted to know about accretion but were afraid to ask: Done, Gierlĭ nski & Kubota 2007A&ARv..15....1D Sec 1 and 2 ONLY-OR Sec 7 only this is a very long article!

2014MNRAS.437.1698 X-ray emission from star-forming galaxies - III. Calibration of the LX-SFR relation up to redshift z ≈ 1.3 Mineo, S.; Gilfanov, M.; Lehmer, B. D

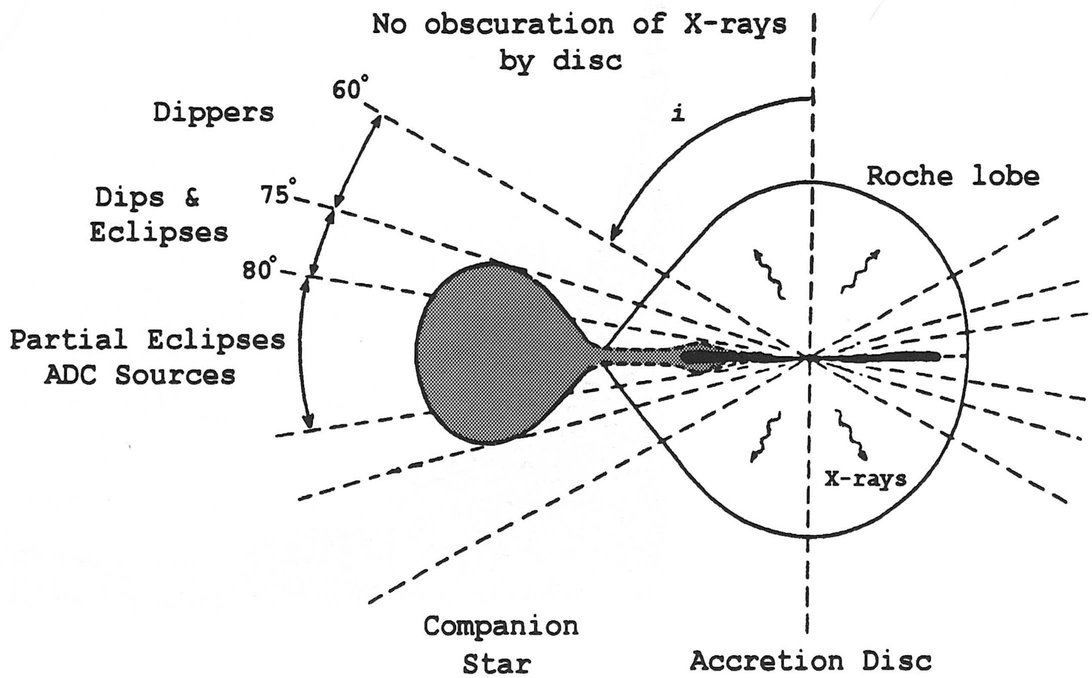
Evidence for strong cyclotron line emission in the hard X-ray spectrum of Hercules X-1: Trümper, J., Pietsch, W., Reppin, C., et al. 1978, ApJ, 219, L105 (503 citations)

- Modern Review Article :"Cyclotron lines in highly magnetized neutron stars R. Staubert et al 1812.03461.pdf" its long do not need to cover secs 4.4,4.5,4.6,5.0,7.0,8.0)

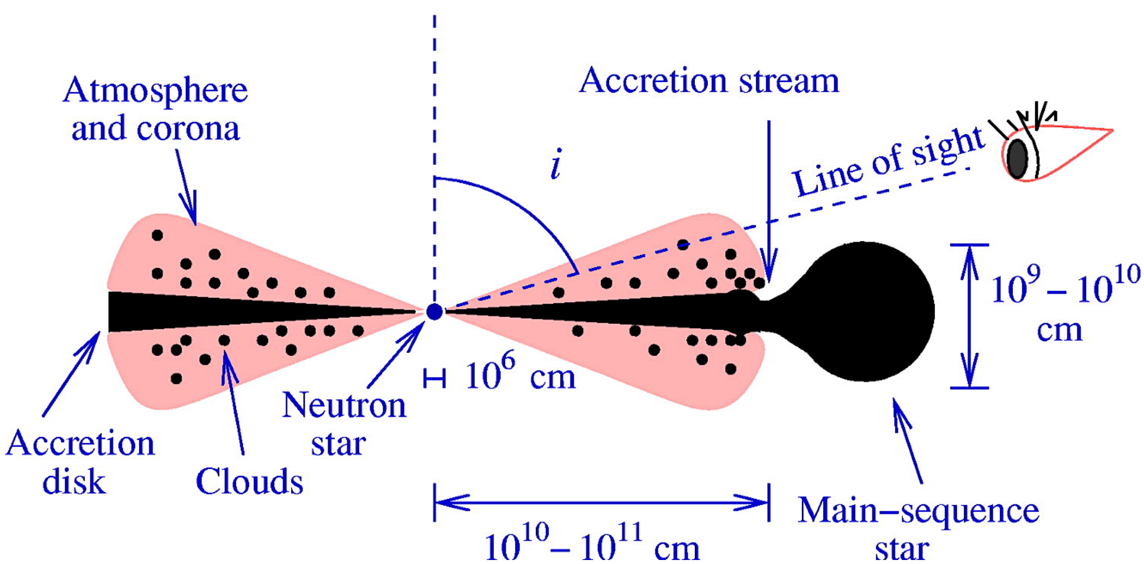
- No one date is strongly preferred - 5 people need to respond
- May 10 has the most
- Please adjust your preferred dates

	Apr 29 MON	Apr 30 TUE	May 1 WED	May 2 THU	May 3 FRI	May 4 SAT	May 6 MON	May 7 TUE	May 8 WED	May 9 THU	May 10 FRI
18 participants	✓10	✓7	✓8	✓6	✓10	✓8	✓11	✓9	✓11	✓9	✓13
Richard Mushotzky											
Ben	✓	✓	✓		✓		✓	✓	✓		✓
Julian		✓					✓	✓		✓	✓
Miléna	✓		✓		✓	(✓)	✓		✓		✓
Sergio	✓				✓				✓		✓
Joe	(✓)	✓	✓			✓	(✓)	✓	✓		
Ramsey						(✓)	✓	✓	✓	✓	✓
Gabe	✓		(✓)				✓		(✓)		
Jason	✓		✓	✓	(✓)	(✓)	✓		✓	✓	(✓)
Jongwon					✓						✓
Tomas					(✓)	✓	(✓)	✓	✓	✓	(✓)
Erica	✓				✓		✓				✓
Zhiyu	✓		✓				✓		✓		
Vivian Carvajal			✓	✓	✓	(✓)			✓	✓	✓
Alex	✓		✓		✓	✓	✓		✓		✓
Teal's Deal		✓		✓		✓		✓		✓	✓
Rye Volpert		✓		✓				✓		✓	
Jonathan Williams		✓		✓				✓		✓	
Charlotte Ward	✓	✓		✓	✓			✓		✓	✓

Effects of Geometry on Observed Properties can be Huge (P.Charles)



Geometry of heated accretion disk + corona in LMXB



Jimenez-Garate et al. 2002

Accreting Magnetic Neutron Stars Longair 14.5.3

Effect of magnetic field

- flow of ionized gas is channeled by the field
- Photon production in a strong field is different (cyclotron radiation)- will not discuss further (see Longair 8.2)- the spectral feature is at an energy E= $(h/2\pi)m_eB$= $11.6B_{12}$keV,where B= $10^{12}B_{12}$G.

Paper to discuss (Discovery paper: Trumper et al 1978 Trümper, J., Pietsch, W., Reppin, C., et al. 1978, ApJ, 219, L105

Modern Review Article :"Cyclotron lines in highly magnetized neutron stars R. Staubert et al 1812.03461.pdf" its long do not cover secs 4.4,4.5,4.6,5.0,7.0,8.0)

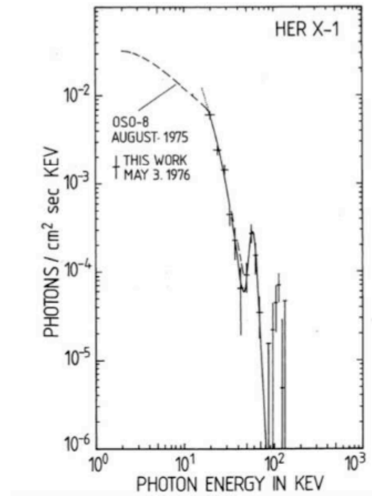


Fig. 1. X-ray spectrum of Her X-1 as obtained in a ba

Accreting Magnetic Neutron Stars

- Effect of magnetic field
  - flow of ionized gas is channeled by the field
  - Photon production in a strong field is different (cyclotron radiation)
- When/where does the magnetic field dominate the accretion flow?

The magnetic energy density is $B^2/8\pi$, and the kinetic energy density of the accreting matter is $1/2\rho v^2$, where ρ is the density and v is the typical velocity. So need $B^2/8\pi < 1/2\rho v^2$

Assume spherical symmetry so accretion rate $\mathcal{M}=4\pi R^2\rho v$; v is on the order of the free fall velocity sqrt(2GM/R); replace R by the Schwarzschild Radius $2GM/c^2$

One gets $B<6\times10^{17}(\mathcal{M}/10^{17}\mathrm{gm/sec})(R/10\mathrm{km})^{-5/4}(M/M_{\odot})^{1/4}$ gauss

If the Magnetic Field is Strong (As In NS Pulsars)

- If magnetic pressure dominates over thermal pressure the magnetic field channels the accretion flow and matter flows along field lines that connect to the magnetic polar regions:
- As a result, almost all of the accretion energy is released in a "hot spot" near the two magnetic poles.
- If the magnetic axis is not aligned with the rotational axis, then as the star rotates we see more or less of the hot spot, and hence see pulsations in the X-rays.

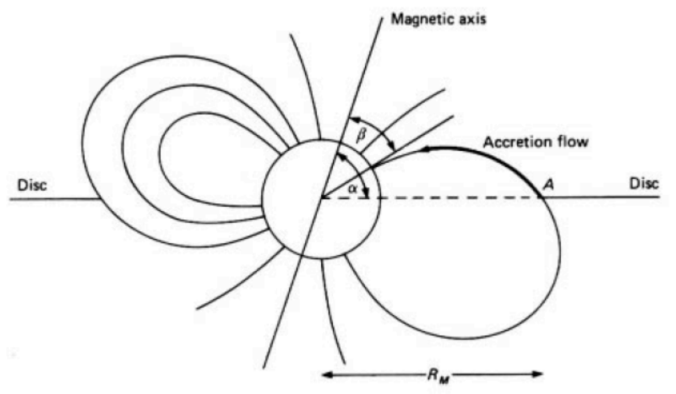


Figure 8: Accretion in a strong ($\sim 10^{12}$ Gauss) magnetic field. Note that the accretion disk is held off the neutron star surface by the centrifugal barrier formed by the rotating magnetosphere.[23]

Longair 14.5.3

Cominsky (2002)

Accreting Magnetic Neutron Stars Longair 14.5.3

- When/where does the magnetic field dominate the accretion flow? (following C. Miller)

- The magnetic energy density is $B^2/8\pi$, and the kinetic energy density of the accreting matter is $1/2\rho v^2$, where ρ is the density and v is the typical velocity.
- For a dipolar field, $\mathbf{B = \mu/r^3}$, (μ is the magnetic moment) and the matter radial free fall velocity is

$v = v_{ff} = \mathrm{sqrt}(2GM/r)$.

Accreting Magnetic Neutron Stars (Cole Miller)

By continuity, $\rho v_{ff} = dM/dt/(4\pi r^2)$ (gas flow) ($dM/dt=\mathscr{M}$)
Magnetic energy density $=B^2/8\pi$

Notice the radial dependences
magnetic energy density goes as r^{-6}
material energy density goes as $r^{-5/2}$.

The magnetic stresses thus increase more steeply with decreasing radius than the material stresses Therefore one expects that far from the star, material stresses dominate

Close to the star, magnetic stresses will dominate if the field is strong enough;

A magnetic moment of $\mu_{30} = 10^{30}$ G cm^3 which gives a surface field of $\sim 10^{12}$ G is typical of neutron stars in high-mass X-ray binaries.

radius of a neutron star is $R \approx 10^6$ cm, the accretion flow onto a strongly magnetized neutron star is dominated by the magnetic field.

Where Does the Magnetic Field Start to Dominate?

the **Alfvén** radius is the radius at which the pressure due to the pulsar's magnetic field equals the ram pressure of infalling material.

So : $\rho v_{ff} = \mathscr{M}/(4\pi r^2)$
The free fall velocity$v_{ff} = (GM_x/2r)^{1/2}$

The Kinetic energy
$E_{kinetic} = 1/2\, \rho v^2_{ff} = \mathscr{M} \sqrt{GM_x} r^{-5/2}/8\pi\sqrt{2}$
The magnetic energy is $E_{mag} = B^2/4\pi = \mu^2/4\pi r^6$
The magnetic field is important for accretion if $\rho v^2_{ff} < (B^2/8\pi)(R/r)^6$
where R is the NS radius and r is the distance from the center

Where Does the Magnetic Field Start to Dominate?

the Alfvén radius is the radius at which the pressure due to the pulsar's magnetic field equals the ram pressure of infalling material.

- Balancing the two one finds that the Alfven radius is
- $r_A = [2\pi^2/G\mu^2_0]^{1/7} \{B^4_s R^{12}_*/M_* \mathcal{M}^2\}^{1/7}$ **eq. 14.60 Longair**

Or putting in typical numbers

- $\mathbf{r_A \sim 3.2\times10^8 \mathcal{M}_{16}^{-2/7} \mu_{30}^{4/7} M_*^{-1/7}}_\odot$ **cm:** notice dependencies
- For a solar mass neutron star accreting at the Eddington luminosity,

$L = \mathcal{M}\eta c^2 = 1.3 \times 10^{38}$ ergs/sec. Adopting $\eta = 0.1$, $B = 10^8$T and $R_* = 10$ km, we have

$r_A = 10^3$ km, ~100 times the radius of the neutron star.

But $r_A \sim r_*$ for a white dwarf

Only if the magnetic field is weak enough can
accretion take place directly onto the surface of the neutron star

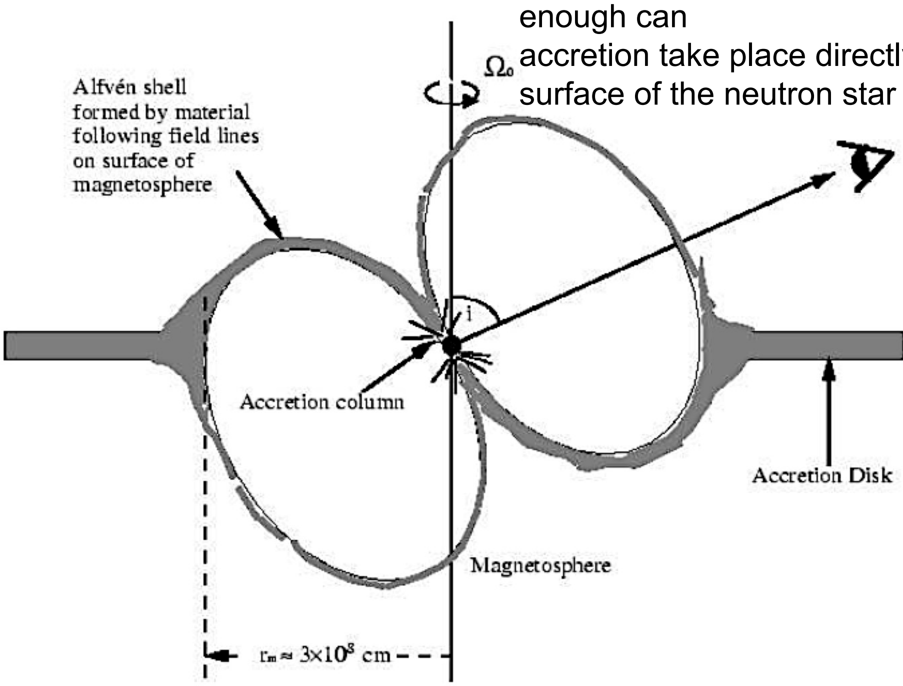
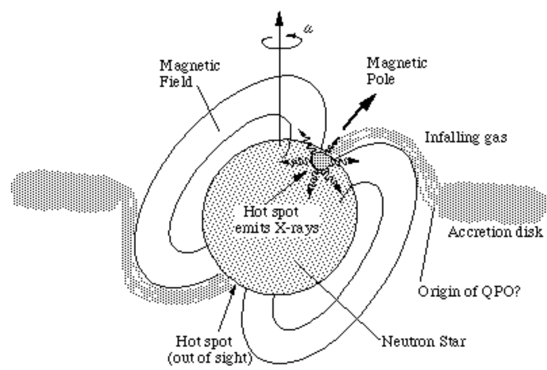


Fig. 1.— Rough sketch of the accretion flow in a disk being picked up by a strong neutron star magnetic field. From http://lheawww.gsfc.nasa.gov/users/audley/diss/img203.gif

- Putting in typical numbers the radius where magnetic and material stresses are equal is the Alfven radius

$$r_A = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7} = 3.2 \times 10^8 \dot{M}_{17}^{-2/7} \mu_{30}^{4/7} \left(\frac{M}{M_\odot}\right)^{-1/7} \text{ cm} .$$

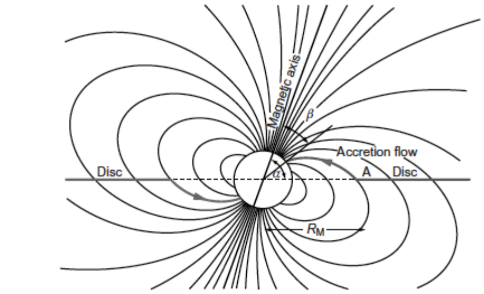
M_{17} is the accretion rate in units of 10^{17} gm/sec- why do we scale it this way??



So How Does Matter Get In??

- For luminous X-ray sources, the immediate vicinity of the neutron star is magnetically dominated
- Matter can, however, be accreted onto the surface of the neutron star, if the matter flows along the magnetic field lines onto the poles of the rotating neutron star
- **releasing the binding energy of the infalling matter as radiation**

in an *accretion column* associated with the infall of matter onto strongly magnetic neutron stars.



An Additional Effect

- If the magnetic field is weak enough to allow a disk to form, but still strong then ...
- Since the magnetic field lines are pinned to the compact object, and have an angular velocity equal to $\Omega*$, the angular velocity with which the compact object rotates.
- At radii $R \geq R_A$, the accreting gas rotates with an angular velocity $$\Omega(R) = (GM_*/R^3)^{1/2.}$$
- At radii $R \leq R_A$, the gas flows along the magnetic field lines, and hence rotates with an angular velocity $\Omega(R) = \Omega_*$.
- For accretion to occur, $\Omega_* \leq (GM_*/R^3{}_A)^{1/2}$
- Numerically, this requires that $\Omega_* < 2\ \mathrm{sec}^{-1} \mu_{30}{}^{-6/7} \mathcal{M}_{16}{}^{3/7} M_*{}^{5/7}$
- $\mathcal{M}_{16}$ in units of 10^{16} gm/sec, M* in solar units, $\mu_{30}$is the magnetic moment of the star, measured in units of10^{30}G cm^3;
- If the NS rotates more rapidly than this, gas will be unable to accrete.(Ryden 2016)

Pulsars

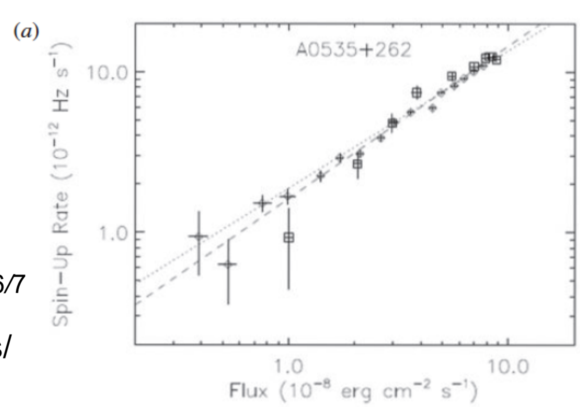
- The rate of change of the pulse period can
  - measure the orbital period of the source
  - The accreted angular momentum (e.g. the amount of material accreted)
- $(dP/dt)/P \sim (L/10^{37})^{6/7}$ (Ghosh and Lamb 1978); Longair 14.62, 14.63

  Spin-up is the result of the torque exerted by the accretion disk on the magnetic field of the neutron star.

The NS is accreting angular momentum from the disk at the rate $\mathcal{M}R^2{}_A\Omega(R_A) = \mathcal{M}(G\mathcal{M}_*R_A)^{1/2}$

$\log_{10} (dP/dt)/P = -4.4 + \log_{10} PL_{37}{}^{6/7}$

L_{37} is the luminosity in units of 10^{37}ergs/sec



Violation of Eddington Limit ??

- The accretion rate of, ~ 0.1 the Eddington limit falls onto a surface area only 10^{-3} of the star !
- So the local flux generated >> Eddington limit
- For such accretion to persist, the radiation cannot escape back up the accretion funnel (remember the incoming material is interacting with the radiation for the Eddington limit to be defined).
- Instead the radiation has to come out where there is little or no accreting material (**out the sides**).
- The Eddington flux is a limit only for spherically symmetric systems, and in this case we have a system that is very aspherical
- the radiation pattern can be a "fan beam" (radiation escaping out the sides), so that we might get two peaks per cycle from the funnel (one from one side, one from the other) as opposed to the one peak we would expect if this were just a thermally glowing hot spot.

Origin of Field ?

- If the field is due to the 'original' star The fields in MS stars are ~1G.
- For a MS progenitor of radius $4\text{x}10^{11}$cm (the sun has a radius of $7\text{x}10^{11}$cm) the star would contain a magnetic flux of ~510^{23} Gcm^2 ($\pi r^2 B$)
- If flux is conserved during the collapse then a neutron star with the same flux would have surface field strength of **$5\text{x}10^{11}$G**, sufficient for a pulsar

- However no one really knows if flux is conserved in the formation of the NS during the Supernova explosion and collapse and there are good reasons to believe that this is not true

Mass of the NS Star- Not in Longair

- In order to measure the mass of the neutron star and its optical companion we need to measure the mass function. For a circular orbit this is

$$f = P_{orb} K^3_O / 2\pi G = M_x^3 \sin^3 i / (M_o + M_x)^2$$

- P is the period of the orbit and i is the inclination of the orbital plane to the line of sight. K_0 is the semi-amplitude of the velocity of the companion star
- f gives a strict lower limit on the mass of the x-ray source

•K_X and P can be obtained very accurately from X-ray pulse timing delay measurements

• K_o is measured from optical spectra for the companion

Orbit

- Sign and phase of the pulses are due to the Doppler effect
- Amplitude of the sine pulse curve gives the size of the orbit (39.75 lt sec) with a 2.09 day orbit
- Eclipses are due to occultations of the NS by its companion
- Circular orbit from shape of time variation of pulses
- Get mass of system and orbital parameters
- Period of 4.8 sec shows that it must be a collapsed object (NS)

$$v \sin i \equiv \frac{Ac}{\tau_0} = 415.1 \pm 0.4 \text{ km s}^{-1} ,$$

$$r \sin i \equiv \frac{T}{2\pi} v \sin i = (1.191 \pm 0.001) \times 10^{12} \text{ cm} ,$$

$$\frac{M^3 \sin^3 i}{(M+m)^2} \equiv \frac{(2\pi)^2}{GT^2} (r \sin i)^3 = (3.074 \pm 0.008) \times 10^{34} \text{ g} .$$

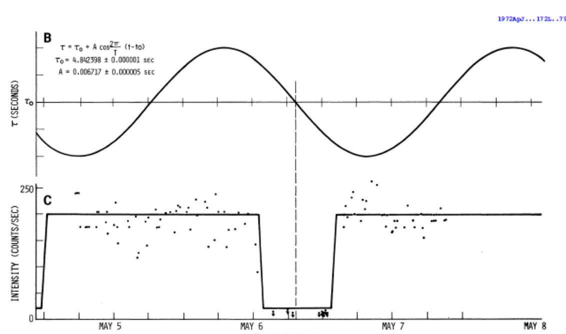


FIG. 4.—Continued

Mass Function- Longair 13.33

- $F(m_1,m_2,i)=m^3{}_1\sin^3 i/(m_1+m_2)^2$
- Re-writing this as

  $M_x=F_x q(1+q)^2/\sin^3$
- q=ratio of the mass of the x-ray star to its companion

- **Using Newton's laws**

$F(m_1,m_2,i)=(P/2\pi G(1-e^2)^{3/2}(v_2 \sin i)^3$

And

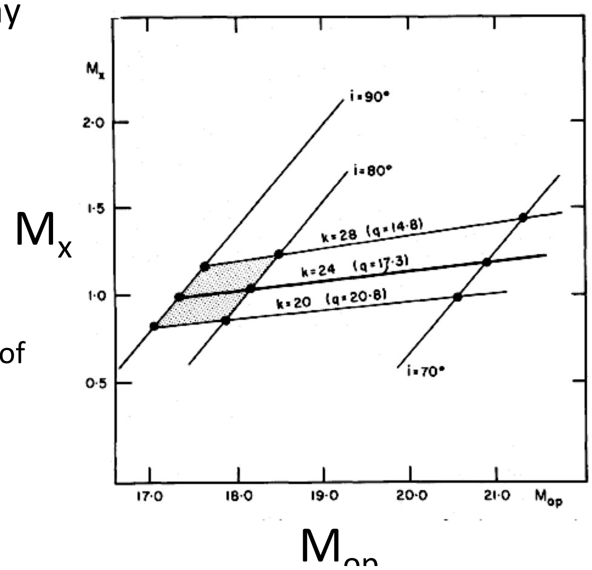
$F(m_1,m_2,i)=(4\pi^2/GP^2)(\alpha_2 \sin i)^3$

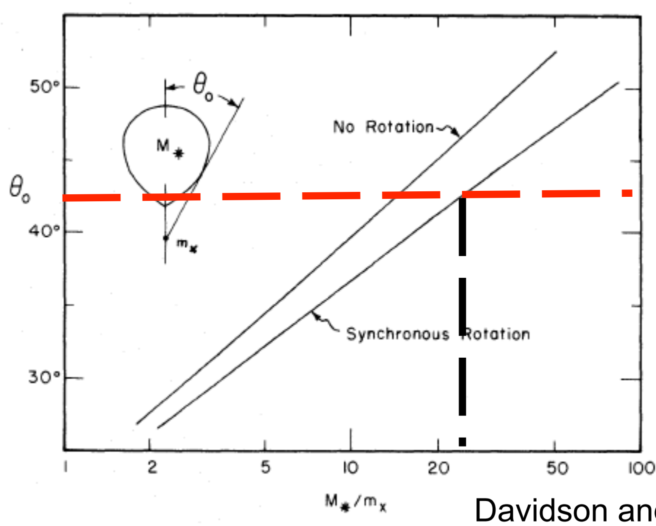
Where a_2 is the orbital semi-major axis of star 2, $v_2\sin i$ is 1/2 the peak to peak orbital velocity of star 2

P is the period and e is the eccenricity

The delays in the observed arrival time of the pulses gives $a_2\sin i/c$ and the period thus $F(m_1,m_2,i)$

The duration of the eclipse tells us about the star size





Davidson and Ostriker 1973

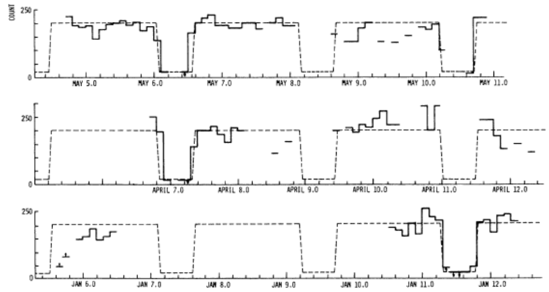
FIG. 1.—Eclipse half-angles in the equatorial plane, for cases in which the eclipsing star is nonrotating and fills its tidal lobe, and in which it rotates synchronously with the binary orbital period and fills its Roche lobe.

- For Cen X-3 he eclipse lasts 0.488 days out of the 2.1 day period or an opening angle of 43 degrees (.488/2.1/2). We know the mass function

$M_*^3 \sin i^3/(Mx+M_*)^2=15$ in this case) M_x ~1

Eclipsing Pulsing Neutron Stars

- A breakthrough in the understanding of these objects was the discovery of eclipses and pulse timing.



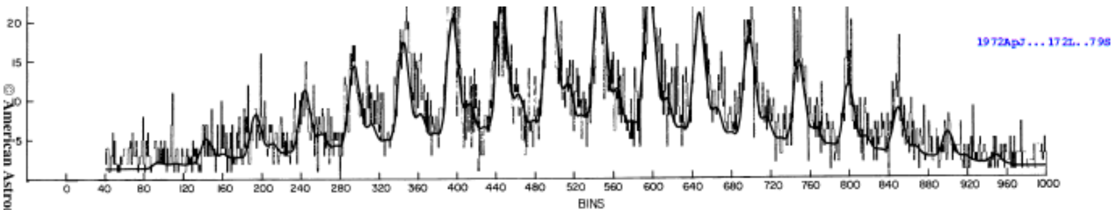


Fig. 3.—The counts accumulated in 0.096 bins from Cen X-3 during a 100-s pass on 1971 May 7 are plotted as a function of bin number. The functional fit obtained by minimizing is also shown.

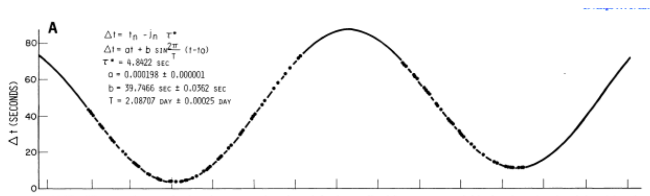
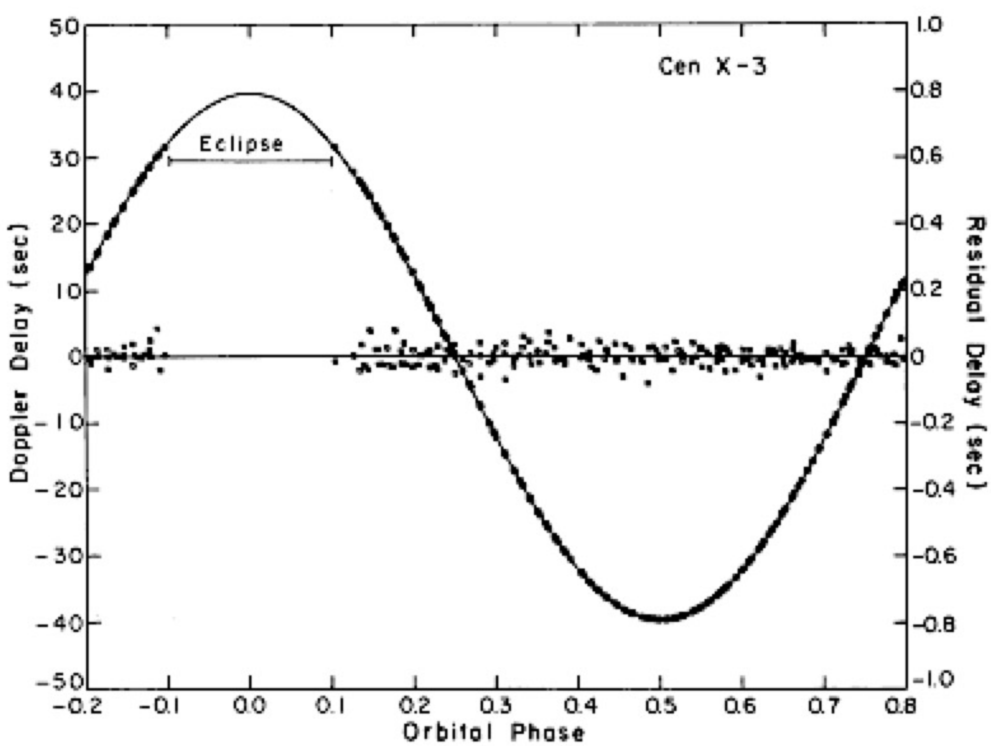
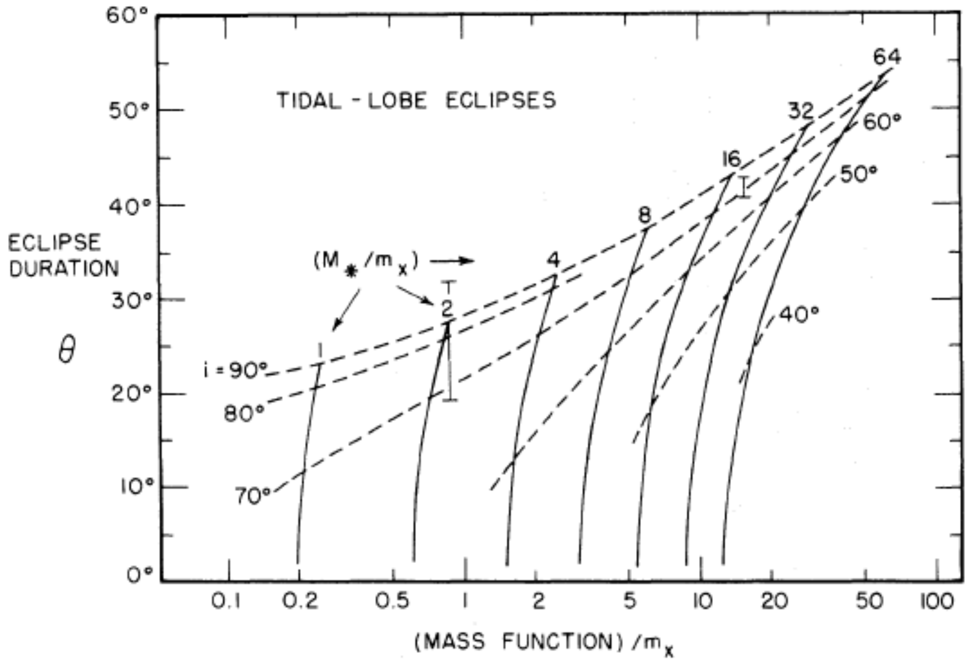


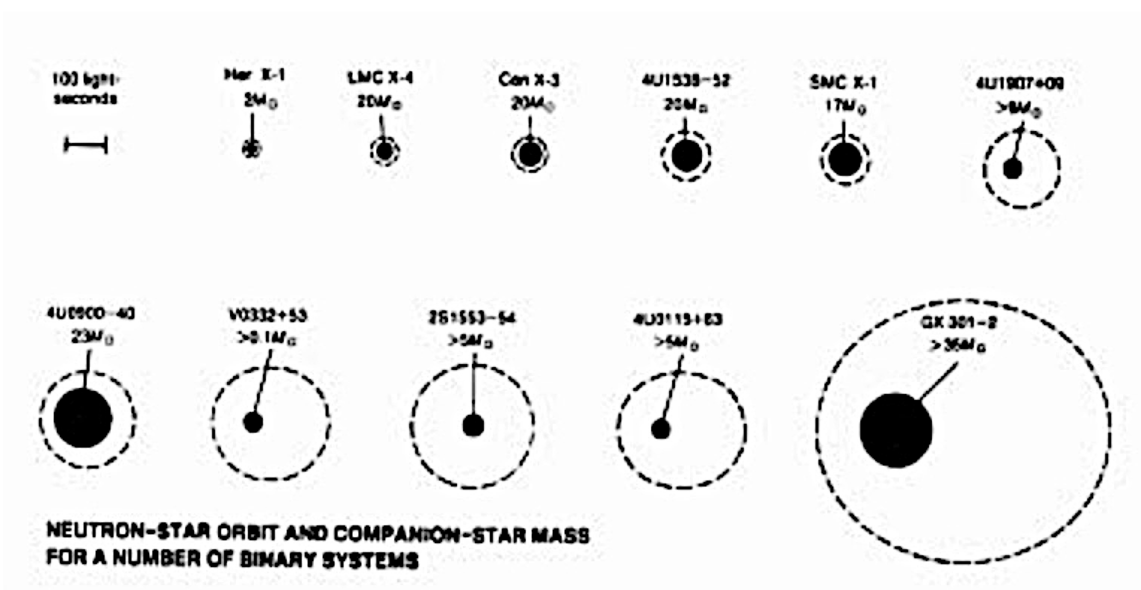
Fig. 4.—(a) The difference Δt between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. A best-fit function and the values of the parameters are given. (b) The dependence of the pulsation period τ on time as derived from the best-fit phase function above is shown and the values of the parameters given. (c) The intensity observed and the light curve predictions are shown for the same set of data. Note the coincidence of the null points of the period function with the centers of the high- and low-intensity states.

Measurement of Orbit Via Pulse Timing





Neutron Star Orbits



NEUTRON-STAR ORBIT AND COMPANION-STAR MASS FOR A NUMBER OF BINARY SYSTEMS

Charles and Seward

How much energy is released by accretion onto a compact object?

- Consider matter in an accretion disk assume that…
  - The matter orbits in circular paths (will always be approximately true)
  - Centripetal acceleration is mainly due to gravity of central object (i.e., radial pressure forces are negligible… will be true if the disk is <u>thin</u>)

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

- Energy is..

$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{GM}{2r}$$