# Accreting Neutron Stars-Mass transfer Fuels Accretion, Creating X-rays

- Two types- based on mass of companions
  - Low mass x-ray binaries-NS star tend to have *low* magnetic field ($B \sim 10^{8\text{-}10}$ G ) and accrete via Roche lobe overflow
  - High mass-NS tends to have *high* magnetic field (($B \sim 10^{11\text{-}13}$ G), accrete from stellar winds

- A bit about observations
  - LMXBs tend to be rather luminous and not show pulsations- spectra are 'quasi-thermal' due to radiation from accretion disk and surface of NS
  - HMXBs are often 'pulsars', spectra are non-thermal dominated by effects of energy generation and transfer in a high B field. Can measure B field via detection of cyclotron emission/absorption features.

$$\hbar\omega_c = \hbar eB/m_e c = 11.6 B_{12} \text{ keV},$$

# Two Modes of Accretion- Longair 14.5.2

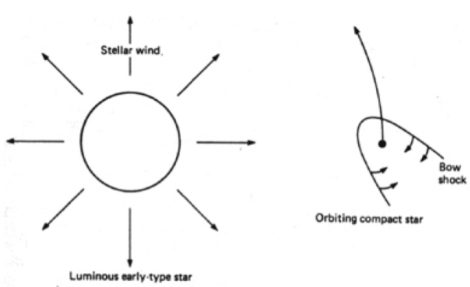



Figure 9: Accretion from a stellar wind.[23]

Accretion from a stellar wind

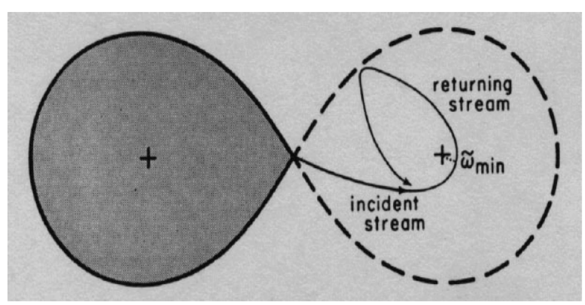



Figure 6: Roche lobe geometry, showing the incident mass stream through the inner Lagrangian point and the intersection of the returning stream with the newly arriving material. The low mass companion on the left hand side completely fills its Roche lobe, while the position of the compact object is denoted by a plus sign (+) inside the right hand lobe.[24]

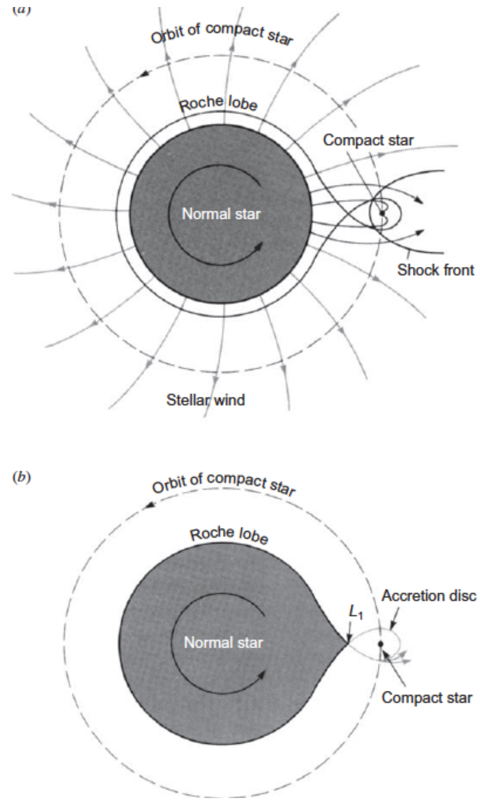
Accretion from Roche Lobe Overflow

Cominsky (2002)

# Two Modes of Accretion – Longair Fig 14.13

- Many stars emit stellar winds, which are very strng in the cases of luminous O and B stars in

  mass loss rates as high as $10^{-5} M y^{-1}$ are observed Top figure the compact companion is embedded in an outflowing stellar wind
- *Roche lobe overflow*. The equipotential surfaces of a close binary star system are distorted in the rotating frame of reference when the stars fill a substantial fraction of the Roche lobe



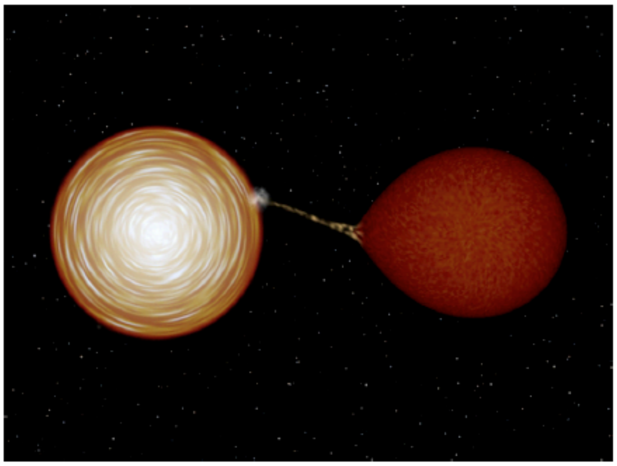

# HMXBs T. Kallman

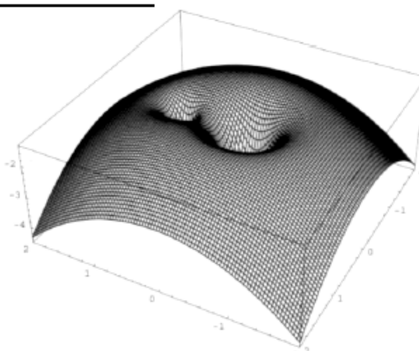
- Among the first discovered extra-solar sources (eg. Vela X-1, Cyg X-1, Cyg X-3, Her X-1)
- Often contain pulsar
- Often eclipsing
- Pulse timing + stellar radial velocity +eclipses = mass, orbital separation, inclination determination
- Accretion can occur from wind from primary, or from Roche-lobe overflow
- Two different subtypes:
  - Be binaries
  - Supergiant binaries
- Statistics: ~50 known in galaxy
- Young population, lifetime ~$10^5$ yrs: mass transfer is unstable- wide range in luminosities

## Roche Lobe Overflow Systems

*Sample*

- Almost all LMXBs and IMXBs
- Small fraction of HMXBs

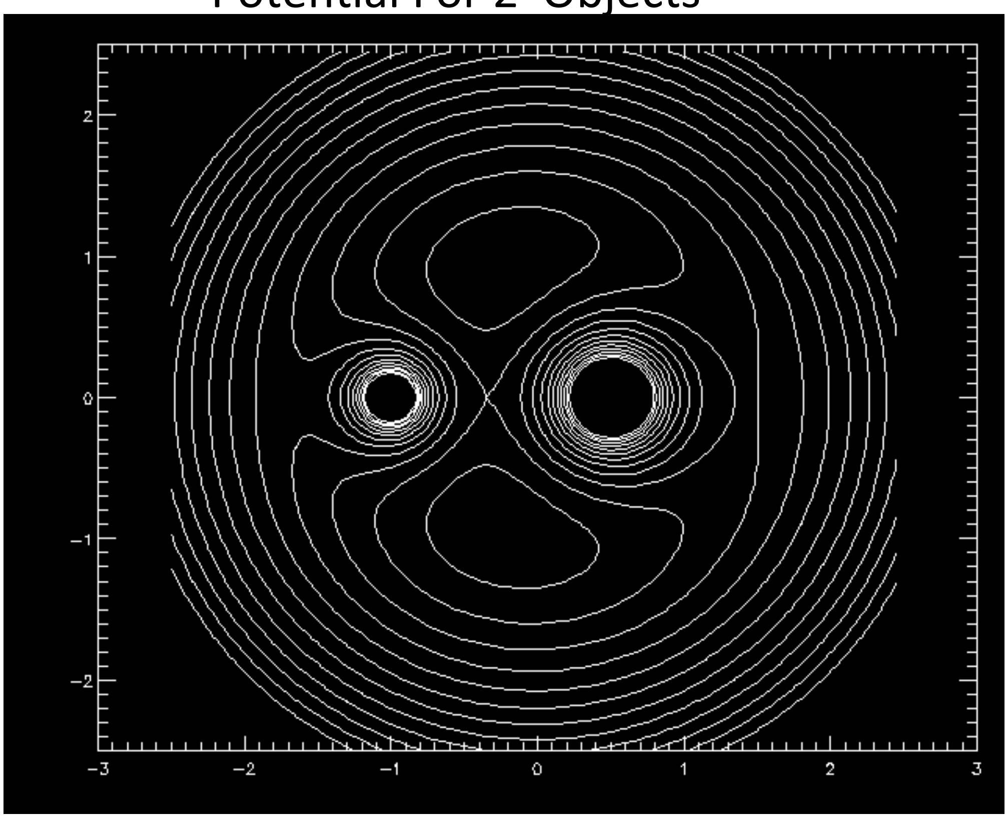




From Frank et al., 2002, Accretion Power in Astrophysics

see http://cronodon.com/SpaceTech/CVAccretionDisc.html for more details

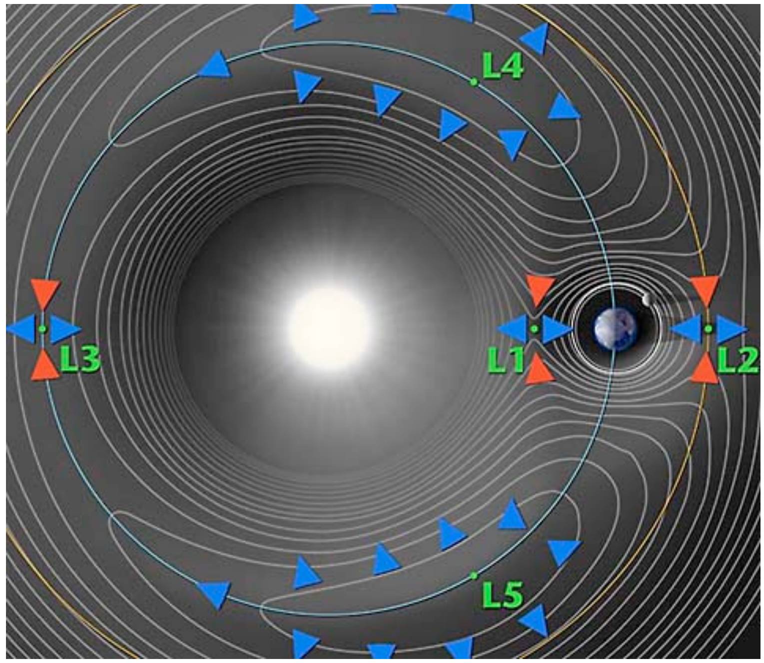
## Potential For 2 Objects



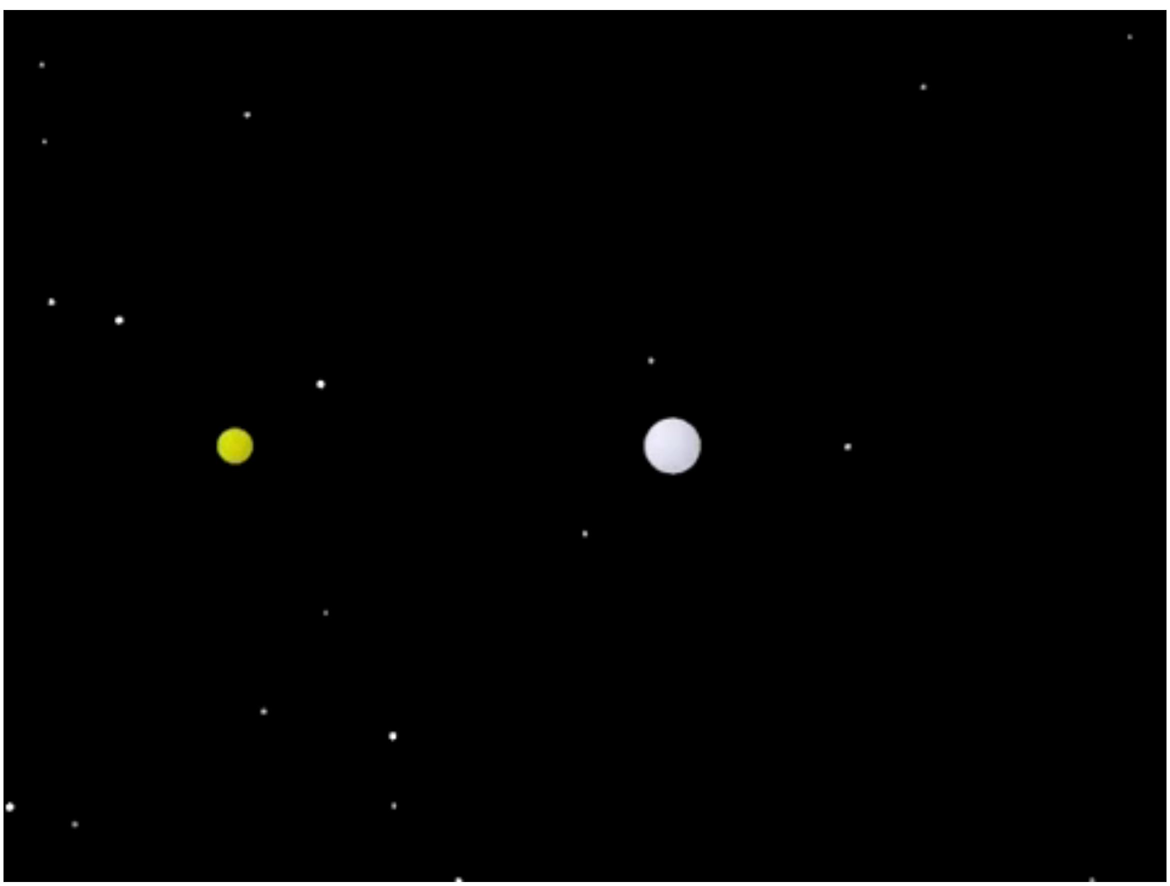
- Gravitational and centrifugal (angular momentum) terms
- ω is the angular momentum
- $\omega = [G\mathcal{M}/a^3]^{1/2}$

- where a is the separation and $\mathcal{M}$ = [ $M_2/M_1+M_2$]

L1 is an unstable Lagarangian pt



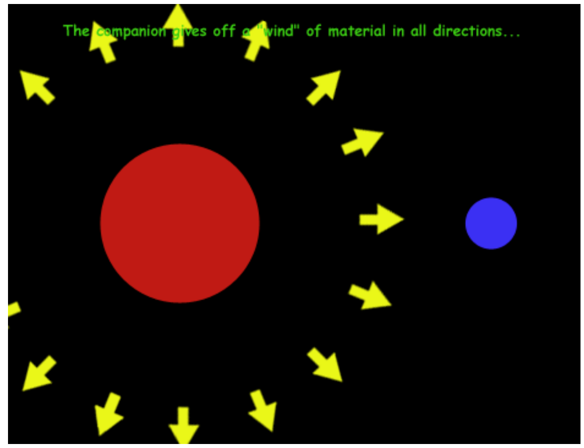

$$\Phi_R = -\frac{GM}{|\mathbf{r}-\mathbf{r_1}|} - \frac{GM}{|\mathbf{r}-\mathbf{r_2}|} - \frac{1}{2}(\omega \times \mathbf{r})^2$$



# High Mass X-ray Binary

The high mass companion sheds mass through a wind.

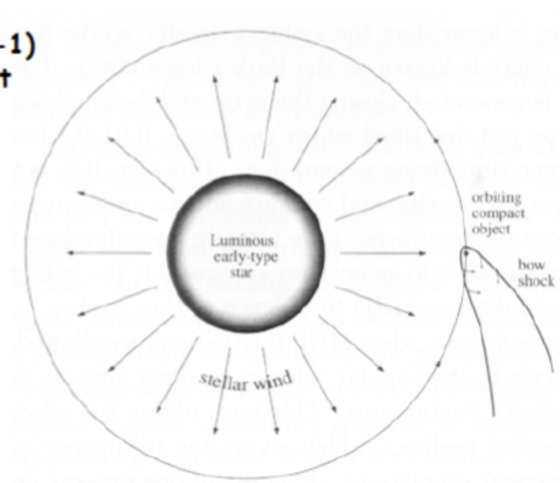
- This wind flows isotropically from the companion, so a portion runs into the compact object.
- This material releases its potential energy as X-rays.




## Wind Fed Systems

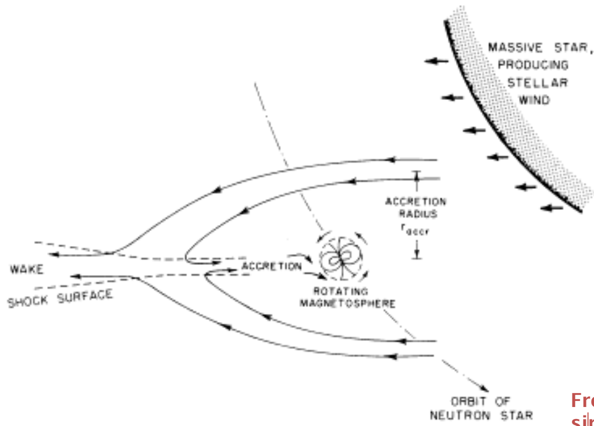
*Sample*

- Some HMXBs with supergiant companions (~1/3 of the systems
- Both persistent (e.g. Vela X-1) and transient (supergiant fast X-ray transients)
- Symbiotic X-ray binaries (e.g. GX 1+4)




From Frank et al., 2002, Accretion Power in Astrophysics

# HMXB- wind accretion




Observed X-ray luminosity

From similar stars

Efficiency Guess: ~0.1

separation

Wind speed

$$L_x \sim \mathscr{M}_{wind}\, c^2 G^2 M^2 \eta \,/(a^2\, v_w^4)$$

Theory of wind accretion:
(Davidson and Ostriker 1973):
$\rho v_w^2/2 = GM\rho/r$

# Accretion From a Wind Longair 14.6.4

- The process is called Bondi accretion
- Consider a star of mass m, traveling through a gas of density ρ at relative velocity $v_{rel}$.
- Material inside a cylinder of radius

$r_{acc}=2GM/v_{rel}^2$ can lose enough energy to fall onto the star at an accretion rate of $S=\pi r^2_{acc} v_{rel} \rho f$ (where f is a fudge factor due to things not properly modeled due to radiation pressure effects and gas dynamics)

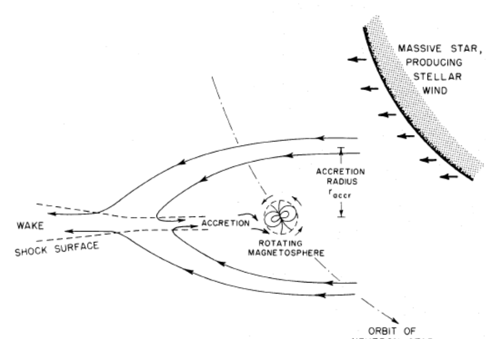


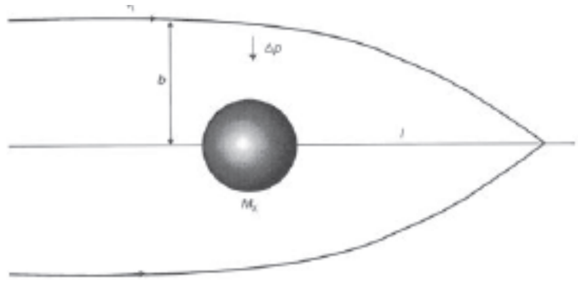

FIG. 3.—Streamlines of stellar-wind material, relative to an accreting neutron sta
dimensions are not to scale.

giant stars stellar wind speeds are ~700km/sec giving

$r_{acc} \sim 5\text{x}10^{10}$cm

# Accretion From a wind – Following Longair

- the impulse which a particle receives on passing a stationary mass is given by the inward force at the distance of closest approach *b* (see 5.2)
- The gravitational force of attraction per unit mass at distance *b* is $GM_X/b^2$ and the duration of this force is $2b/v_t$. The momentum impulse inwards is
- $\delta p = 2GM_X/bv_t$



process of accretion by a star of mass $M_X$ in a stellar wind of velocity $v_t$.

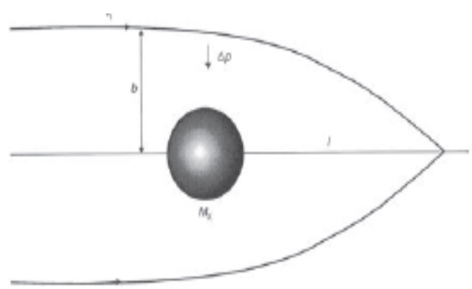
At distance $l$ downstream,the particles with collision parameter *b* collide on the axis of the flow. The perpendicular component of the velocity goes to zero and the condition that the matter be captured by the star is gravitational potential energy of matter at $l$ be greater than its KE outwards $\sim 1/2 v_t^2$

**Giving a capture radius**

$R_c = 2GM_X/[v_x^2 + v_w^2]$

# Accretion From a wind – Following Longair

- $L_X \approx [\eta \dot{m}_P / 4] (2GM_X/R_P)^2 \mathbf{v_w}^{-4}$
- $\dot{m}_P$ the mass loss rate from the donor star
- accretion rate is $\sim(\dot{m}_P/4)(R_c/R_p)^2$
- $R_p$ is the distance of the compact object from the donor star
- $R_c$ is the critical (capture radius)
- **Wind velocity $v_w$>> orbital velocity $v_x$**



of accretion by a star of mass $M_X$ in a stellar wind of velocity $v_t$.

**So** X-ray luminosity is directly proportional to the mass-loss rate of the donor star, $\dot{m}_P$ , and is very sensitive to the wind velocity

# 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.

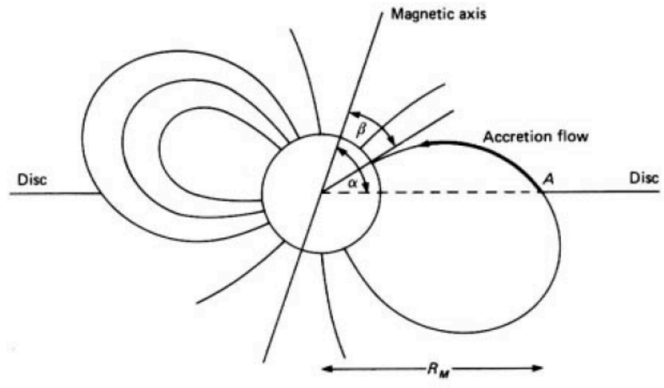


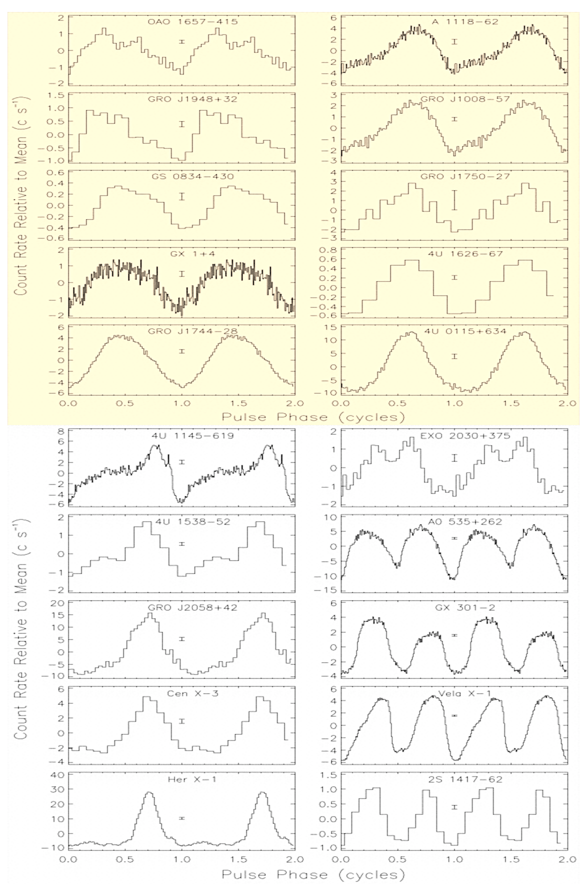

Figure 8: Accretion in a strong ($\sim 10^{12}$ Gauss) magnetic field. Note that the accretion disk is held off the neutron star surface by the centrifugal barrier formed by the rotating magnetosphere.[23]

Longair 14.5.3

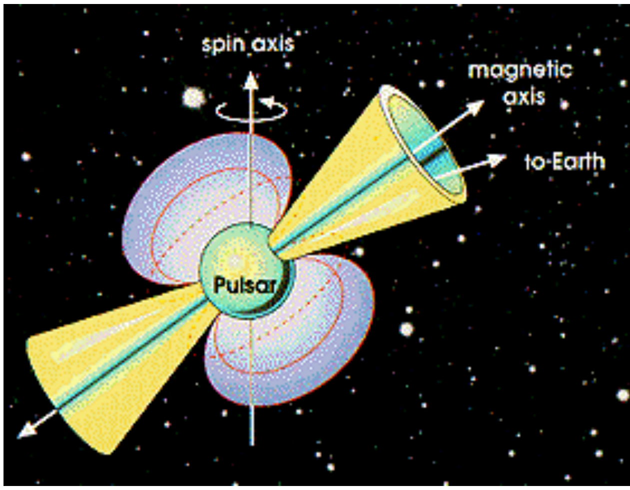
Cominsky (2002)

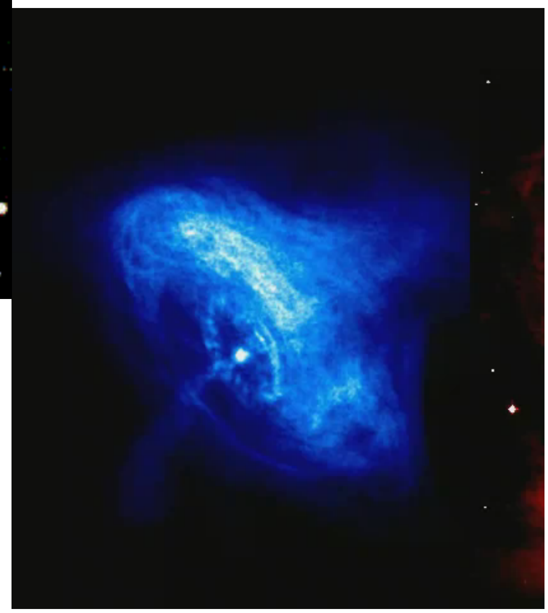
# X-ray Pulsars

- Accrete matter through wind or via disk from a high mass companion. Because of a large magnetic field strength (typically $10^{12}$ G) the material is channeled onto small spots at the magnetic poles.
- the relativistically moving plasma is decelerated in a radiative shock near the surface and settles subsonically
  - **plasma radiates in the X-ray band**
- Pulsations are observed if the magnetic field is inclined relative to the rotation axis.
- Studies of the pulse profiles of individual pulsars allow one to constrain the emission pattern of the hotspots (or accretion columns) at the NS surface as well as the geometry of the magnetic field

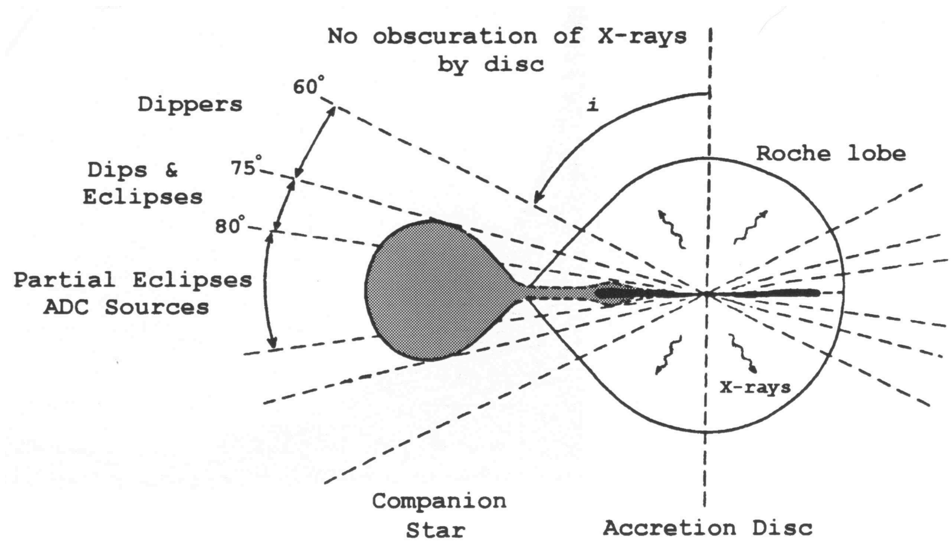


## Rotating magnetic field model



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



# 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)
- 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 $\rho$ is the density and v is the typical velocity.

For a dipolar field, $\mathbf{B = \mu/r^3}$, ($\mu$ is the magnetic moment) and the matter radial free fall velocity is

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

# Accreting Magnetic Neutron Stars

By continuity, $\rho v_{ff} = dM/dt/(4\pi r^2)$ (gas flow) ($dM/dt=\mathcal{M}$ )

Magnetic energy density $=B^2/8\pi$

Notice the radial dependences

magnetic energy density goes as $r^{-6}$

material energy density goes as $r^{-5/2.}$

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 ~$10^{12}$ 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 : $\rho v_{ff} = \mathcal{M} / (4\pi r^2)$

The free fall velocity $v_{ff} = (GM_x/2r)^{1/2}$

The Kinetic energy

$E_{kinetic} = 1/2\, \rho v^2_{ff} = \mathcal{M}\, \sqrt{GM_x}\, r^{-5/2} / 8\pi\sqrt{2}$

The magnetic energy is $E_{mag} = B^2/4\pi = \mu^2/4\pi r^6$

## 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

$\mathbf{r_A \sim (\mu^4 / G M_x \mathcal{M}^2)^{1/7}}$ **eq. 14.60**

Or putting in typical numbers

$r_A \sim 3.2 \times 10^8\, \mathcal{M}_{17}^{2} \mu_{30}^{4/7} M^{1/7}_{\odot}$ cm: **since a NS has a typical radius of $10^6$ cm the magnetic field controls the flow at relatively large radii ($10^8 >> 10^6$)**

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

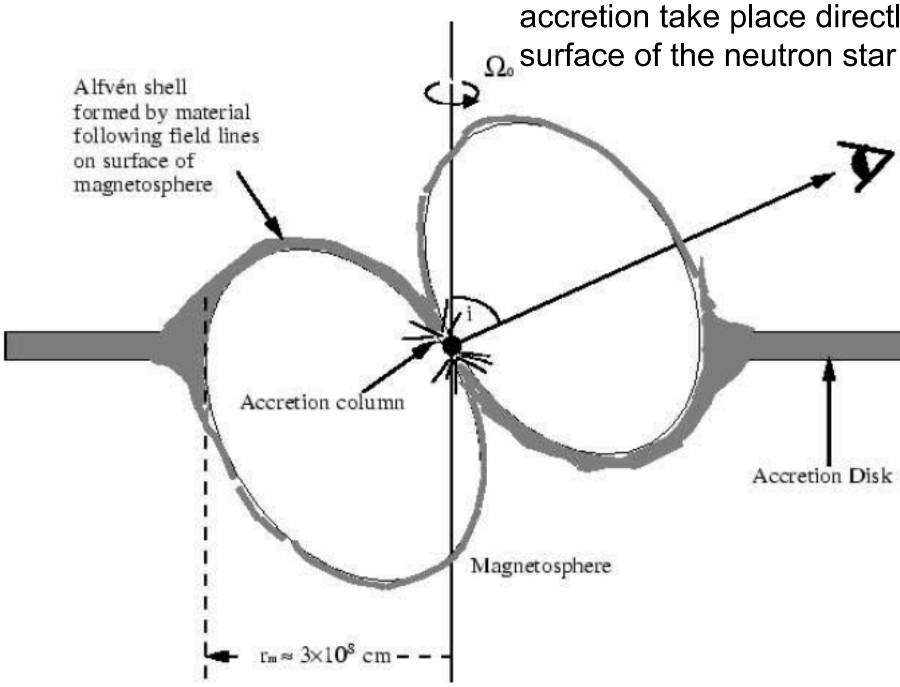
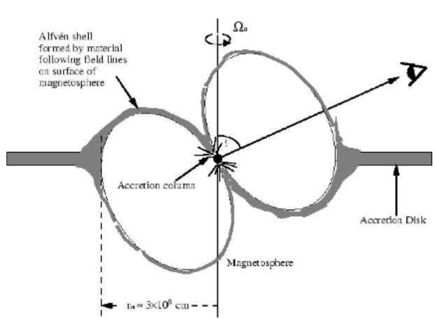



Fig. 1.— Rough sketch of the accretion flow in a disk being picked up by a strong neutron star magnetic field. From http://lheawww.gsfc.nasa.gov/users/audley/diss/img203.gif

- 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??



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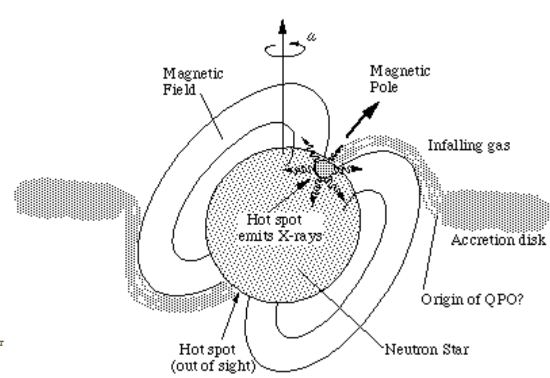
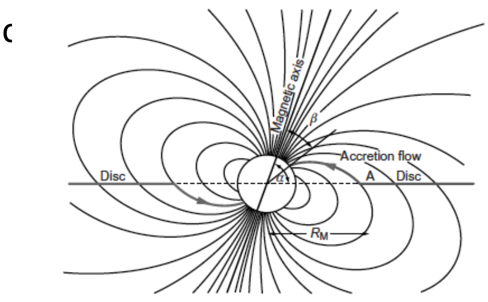


# So How Does Matter Get In??

- 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




# Violation of Eddington Limit ??

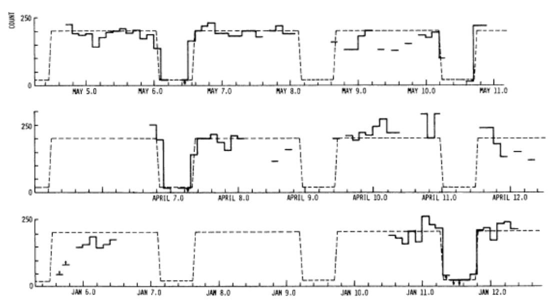
- The accretion rate of, ~ 0.1 the Eddington limited accretion rate falls onto a surface area only $10^{-3}$ of the star !
- So the local flux generated >> Eddington limit
- For such accretion to persist, the radiation cannot escape back up the accretion funnel (remember the incoming material is interacting 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 $4 \times 10^{11}$cm (the sun has a radius of $7 \times 10^{11}$cm) , ($10M_\odot$) 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 $5 \times 10^{11}$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

## Eclipsing Pulsing Neutron Stars

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



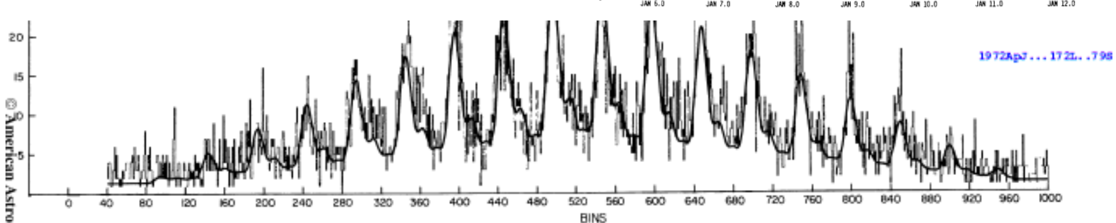






FIG. 3.—The counts accumulated in 0.096 bins from Cen X-3 during a 100-s pass on 1971 May 7 are plotted as a function of bin number. The functional fit obtained by minimizing is also shown.

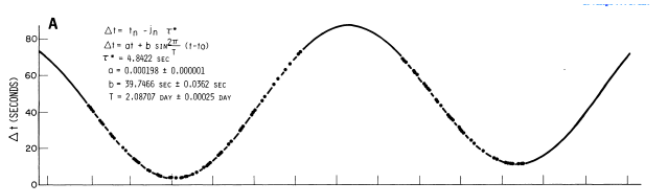



FIG. 4.—(*a*) The difference $\Delta t$ between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. A best-fit function and the values of the parameters are given. (*b*) The dependence of the pulsation period $\tau$ on time as derived from 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.

# 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)

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

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

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

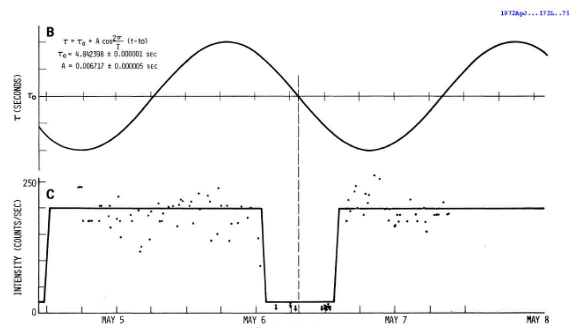
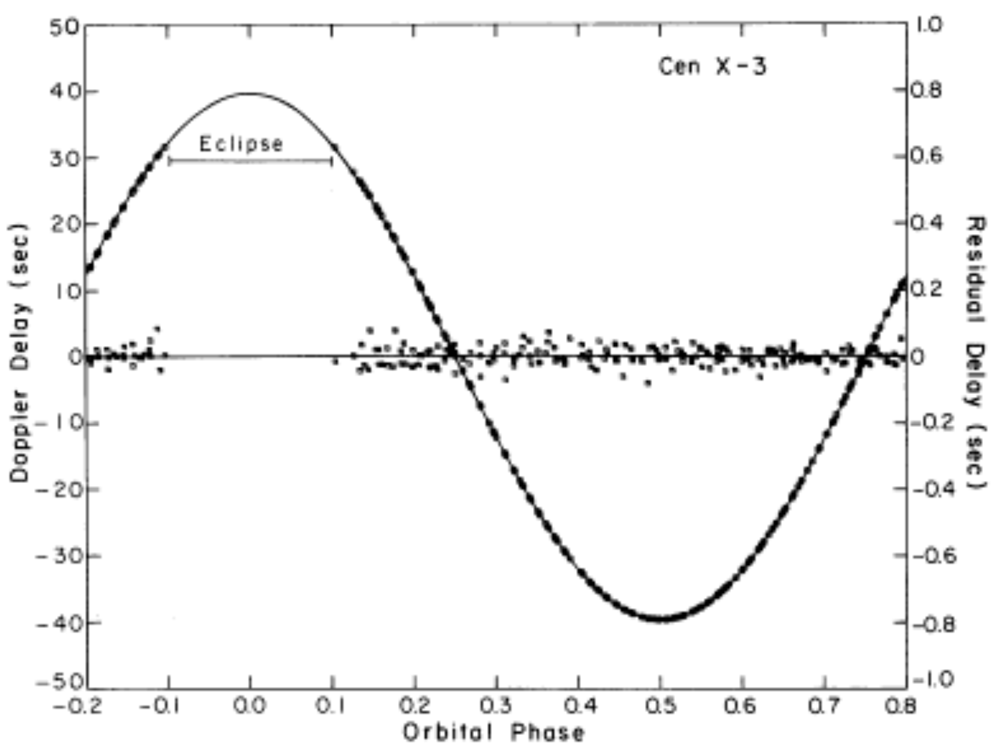



FIG. 4.—*Continued*

# Measurement of Orbit Via Pulse Timing



# 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 it can be shown that this is defined

$M_X = K^3_O P/2\pi G \sin^3 i\ (1 + K_X/K_O)^2$

- $M_O$ and $M_X$ are the mass of the optical component and the X-ray source, respectively,
- $K_X$ AND $K_O$ are the semi-amplitude of the radial velocity curve for the x-ray and optical companion,
- P is the period of the orbit and i is the inclination of the orbital plane to the line of sight.

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

• $K_o$ is measured from optical spectra for the companion

# 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

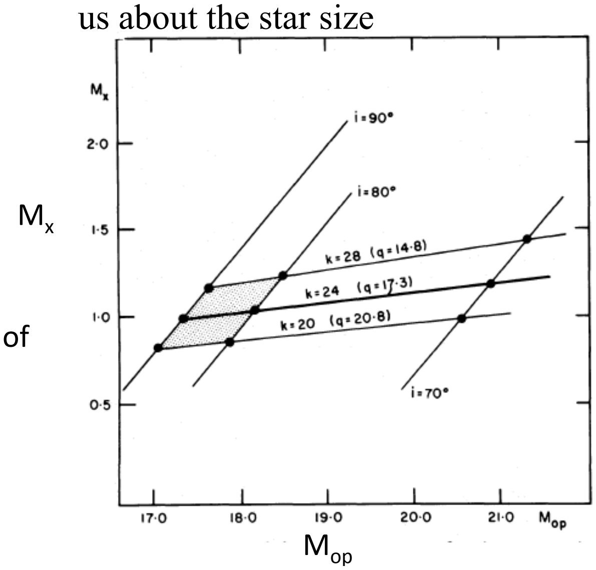
$F(m_1,m_2,i)=(4\pi^2/GP^2)(\alpha_2 \sin i)^3$

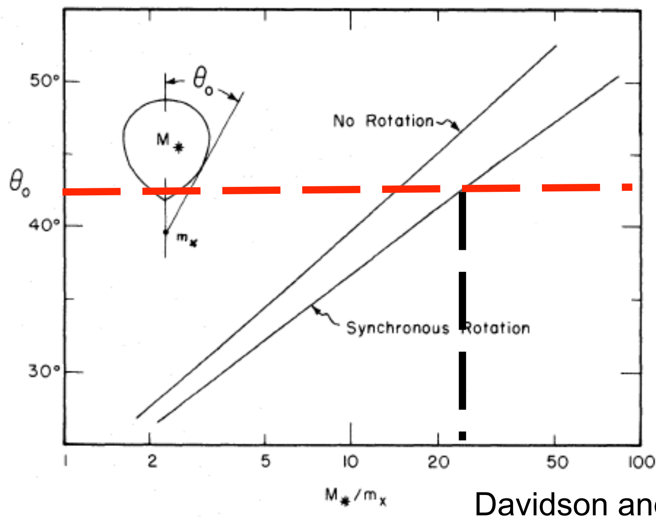
Where $a_2$ is the orbital semi-major axis of star 2, $v_2\sin i$ is 1/2 the peak to peak orbital velocity of star 2

**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



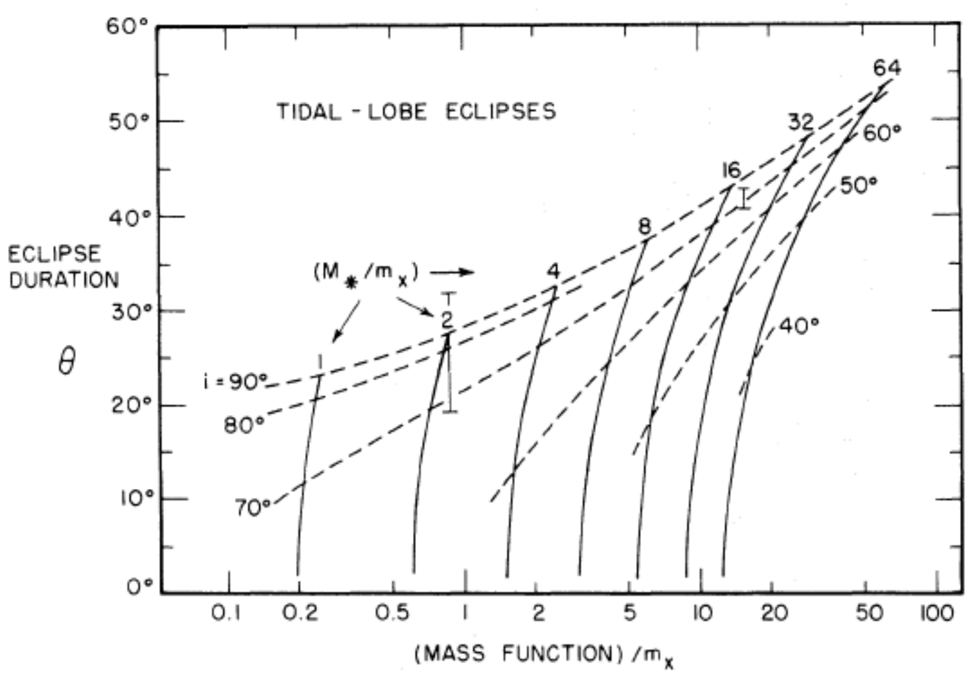



Davidson and Ostriker 1973

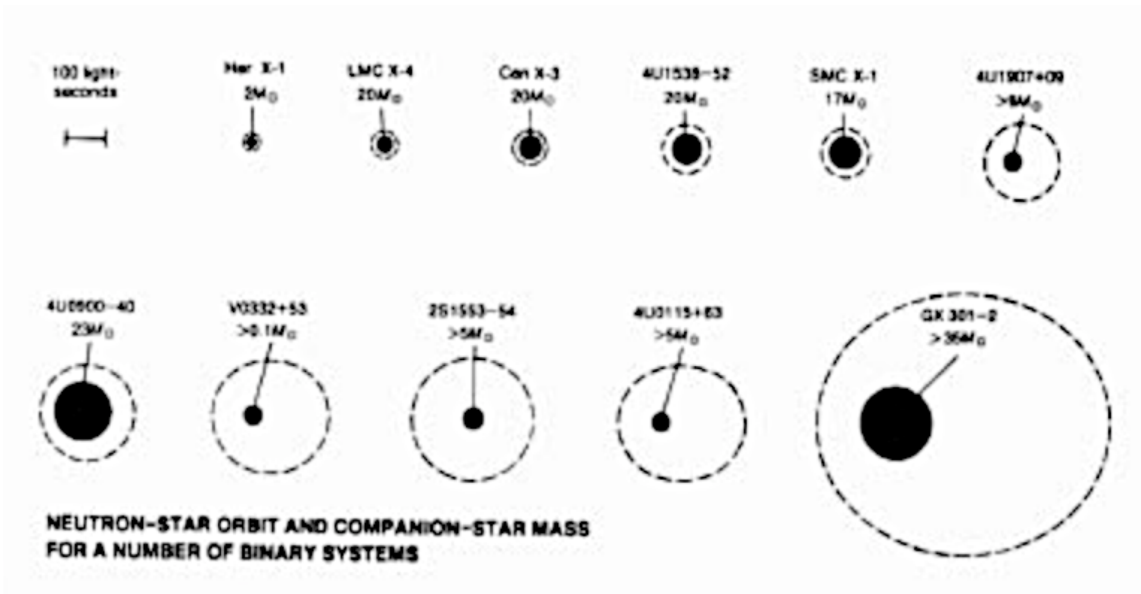
FIG. 1.—Eclipse half-angles in the equatorial plane, for cases in which the eclipsing star is nonrotating and fills its tidal lobe, and in which it rotates synchronously with the binary orbital period and fills its Roche lobe.

- For Cen X-3 he eclipse lasts .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



# Neutron Star Orbits




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

Charles and Seward

# summary

- X-ray binaries exhibit a wide range of behaviors, but much of the interesting physics/astrophysics is common to all
- Understanding of accretion disks, accretion flows, X-ray induced winds, compact object evolution are all in an active  state of research.

## This is a vast field - here are some references for further reading

- Dippers: Smale et al. 1988 MNRAS 232 647
- Black hole transient lmxbs:  Remillard and McClintock, 2006 ARAA 44, 49
- Color-color diagrams for atoll/Z sources : Hasinger and VanderKlis 1989
- Microquasar GRS 1915+105: Mirabel and Rodriguez 1995 PNAS 92 11390
- ADC sources:  White and Holt 1982 Ap. J. 257 318
- Iron line from Cyg X-1:  Miller et al. 2003 Ap. J. 578, 348
- Cyg X-3 Chandra HETG: Paerels et al. 2000 Ap. J. 533, 135
- Accretion disk corona modeling: Jimenez-Garate et al. 2002 Ap. J. 558, 458
- 4U1822-37 spectrum :Cottam et al., 2001 Ap. J. 557, 101
- 'Accretion power in Astrophysics' Frank, King and Raine
- Catalog of X-ray Binaries, Liu Van Paradijs and Lewin 2007 A&A 469, 807
- GRO J1655 chandra spectrum:  Miller et al., 2006 Nature 441, 953
- Hydrodynamics of HMXB winds:  Blonding 1994 Ap. J.

## Downwards to Black Holes!

- The maximum mass of a neutron star
- Complete gravitational collapse to a black hole
- Basic anatomy of a black hole
- Observational discovery of black holes