3.1 The Nature of the Compact Object

The most reliable method to determine the nature of the compact object is the study of the Doppler shift of absorption lines in the spectrum of its companion. The study of the changing radial velocity during the orbital motion is a technique that has been applied for more than one hundred years to measure the masses of stars in binary-systems. The same method is applied for systems like X-ray binaries, where one component is "invisible". In this case the variations of the radial velocity of the normal companion during its orbit are studied.

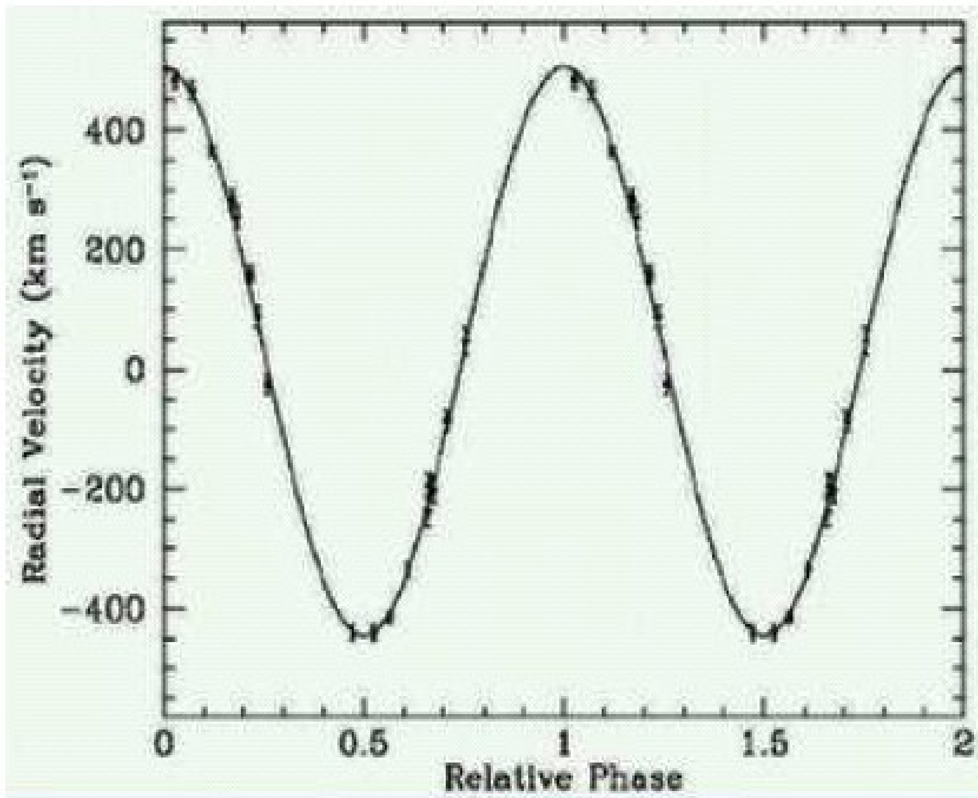
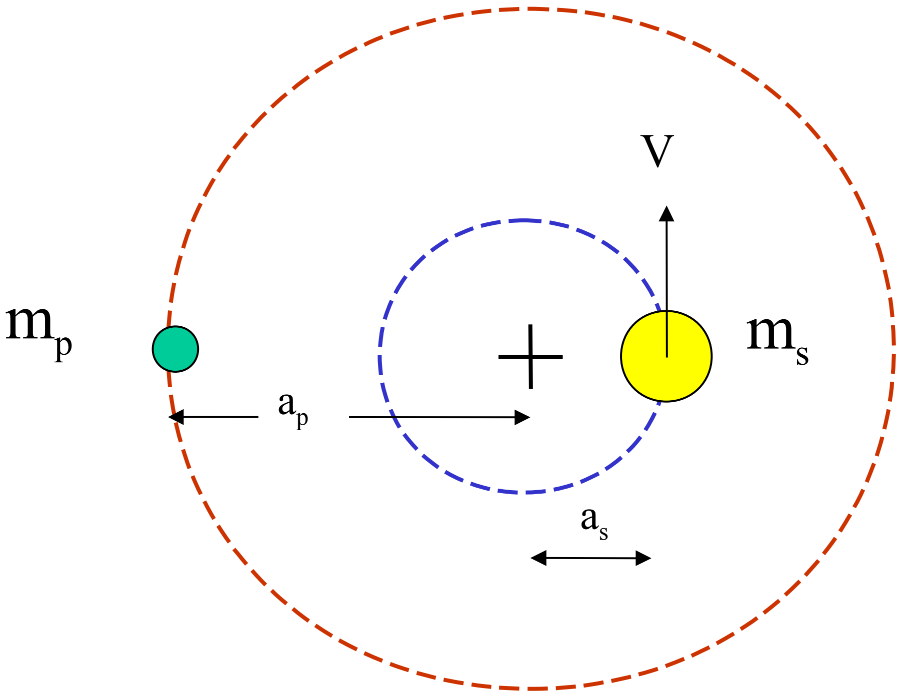


Figure 6: : **Amplitude of the radial velocity variations versus orbital** phase(Filippenko et al. 1999; GRS 1009-45). Using the Doppler shift of spectral



$$P^2 = \frac{4\pi^2 (a_s + a_p)^3}{G(m_s + m_p)}$$

Measuring Masses of Compact Objects

Dynamical study: compact object$_x$ and companion star$_c$

(for binary period, P, and inclination angle, i)

Kepler's 3rd Law: $4\pi^2 (a_x + a_c)^3 = G P^2 (M_x + M_c)$

center of mass: $M_x a_x = M_c a_c$

radial velocity amplitude $K_c = 2\pi a_c \sin i \; P^{-1}$

"Mass Function": $f(M) = P K^3 / 2\pi G = M_x \sin^3(i) / (1 + M_c/M_x)^2 < M_x$

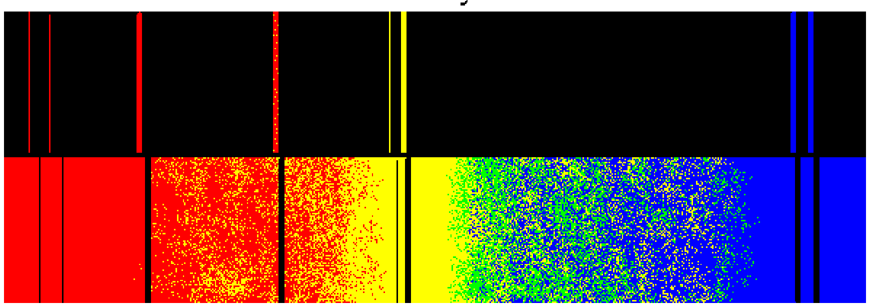
Dynamical Black Hole: $M_x > 3\ M_o$ (maximum for a neutron star)

BH Candidates: no pulsations + no X-ray bursts + properties of BHBs

Doppler shifts

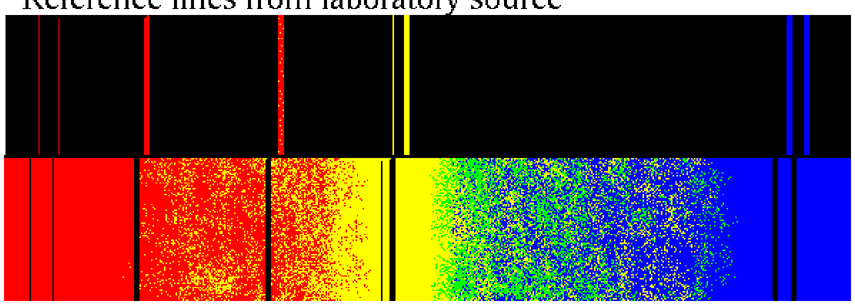
Doppler shifts of the spectral lines yield the radial (i.e. toward the observer) velocity of the star

Reference lines from laboratory source



Absorption lines from star

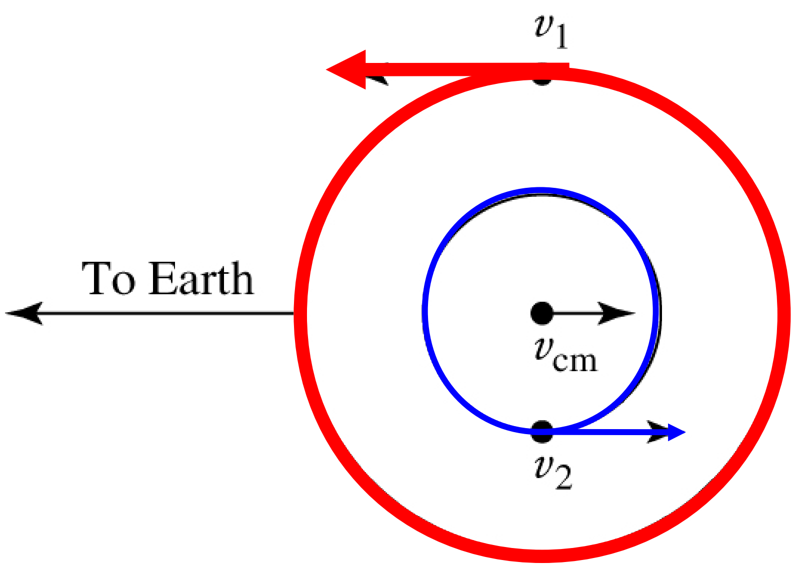
Reference lines from laboratory source

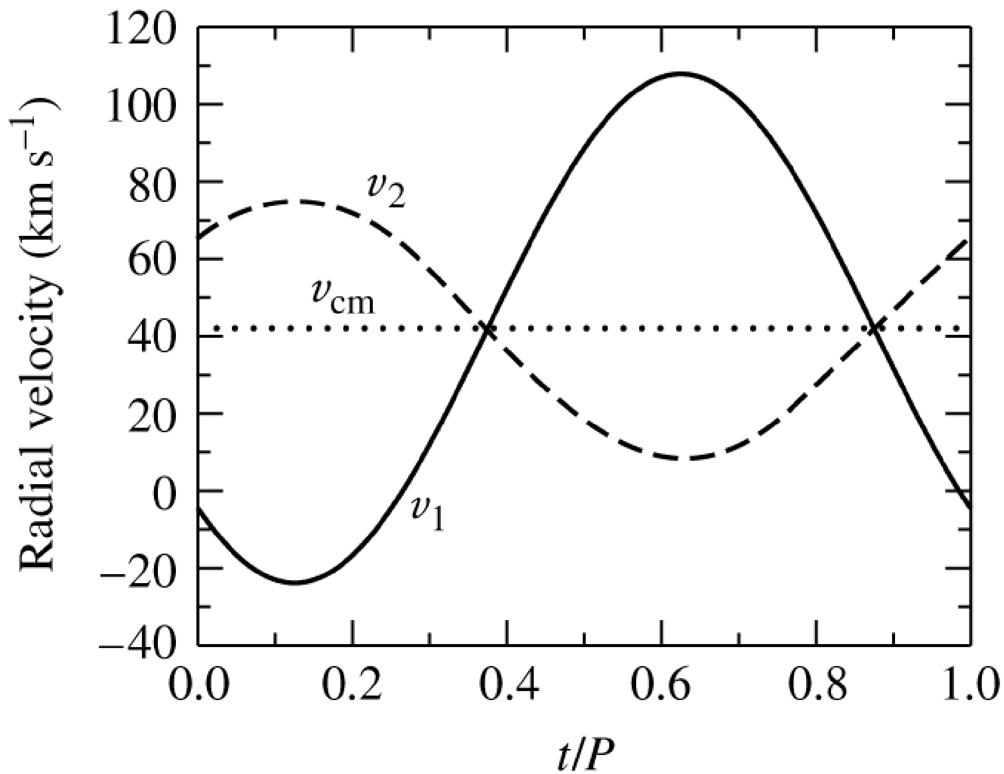


Absorption lines from star

$$z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda_{rest}}$$

$$\frac{v_r}{c} \approx z \quad \text{if } z << 1$$



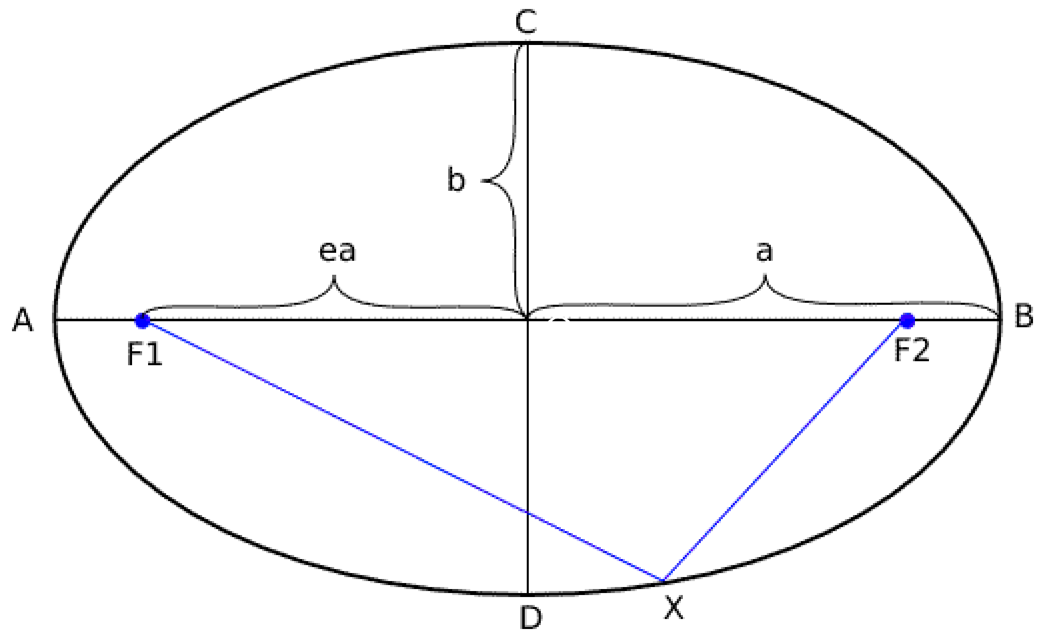


- If the orbit is in the plane of the sky (*i=0*) we observe *no radial velocity.*
- Otherwise the radial velocities are a sinusoidal function of time. The minimum and maximum velocities (about the centre of mass velocity) are given by

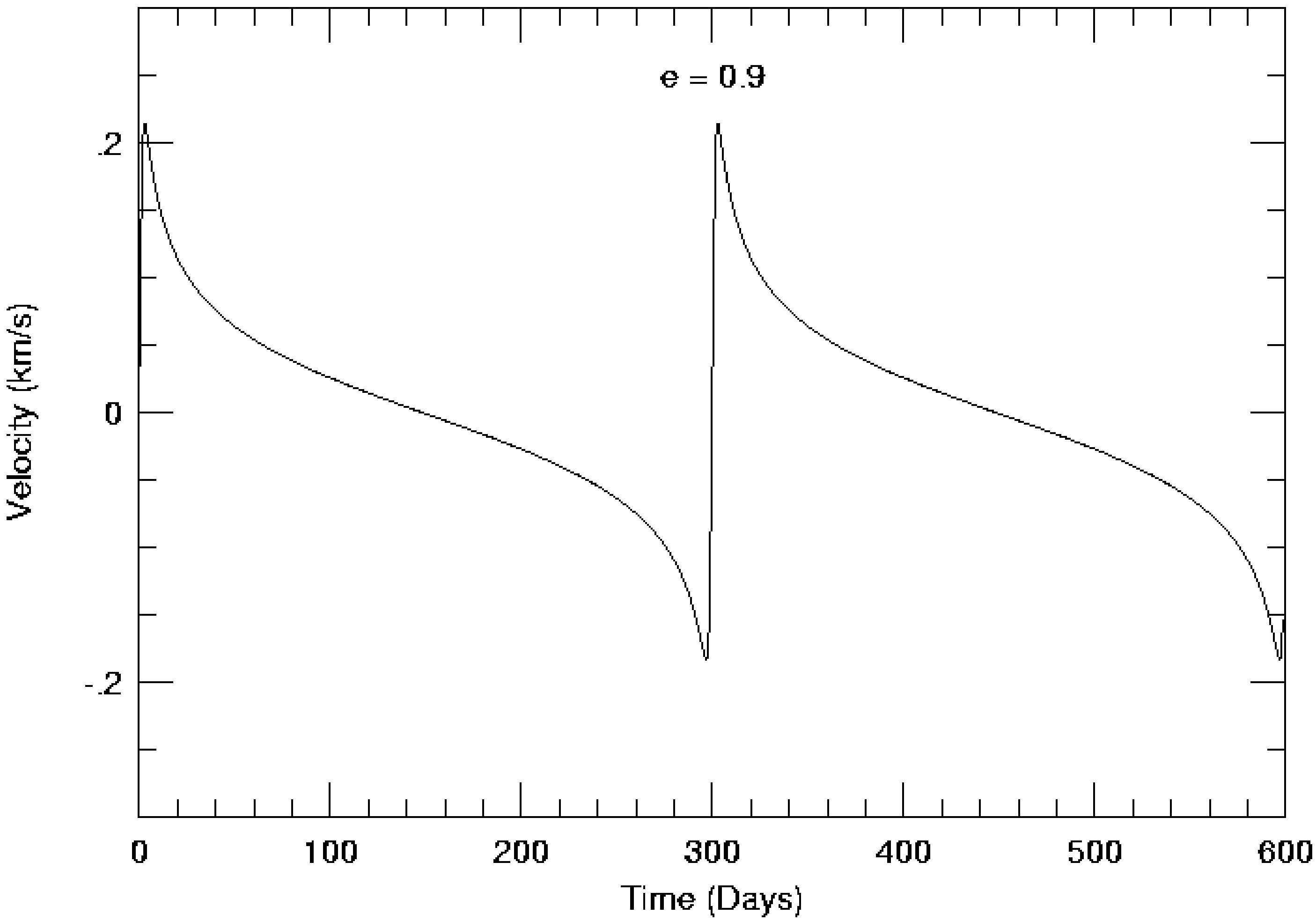
$$v_{1r}^{\max} = v_1 \sin i$$

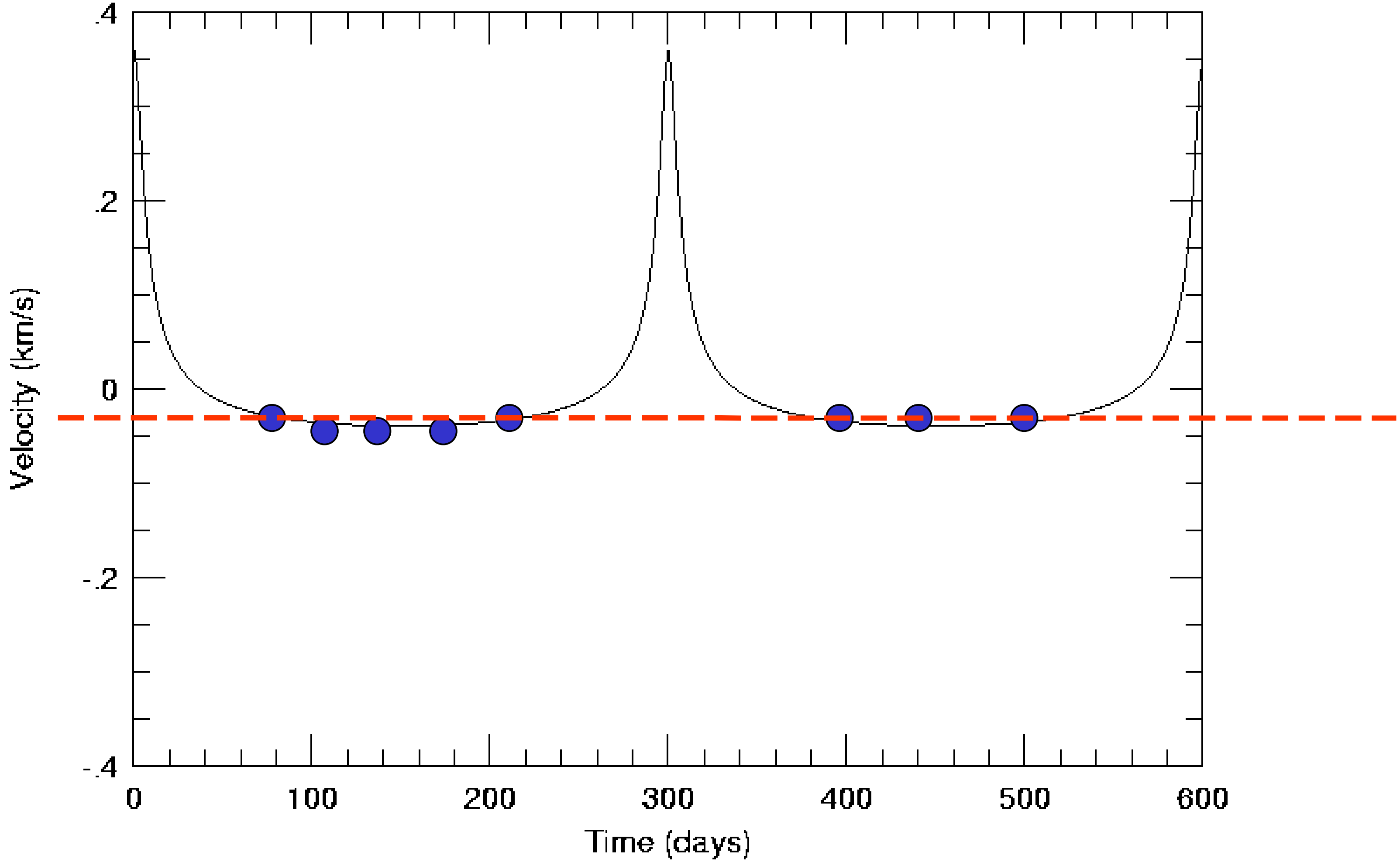
$$v_{2r}^{\max} = v_2 \sin i$$

Elliptical Orbits



Radial velocity shape as a function of eccentricity:





.4
.2
0
-.2
-.4
Velocity (km/s)
0
100
200
300
400
500
600
Time (days)

Mass Function

mass M_1 and M_2 with orbital period P

(semi major axis a_1 and a_2 with $a_1 M_1 = a_2 M_2$)

seen under an inclination angle ***I***

radial velocity of component 1 is seen to with amplitude K_1

for a circular orbit

$$K_1 = 2\pi a_1 \sin i / P_b.$$

using Kepler's laws

expressed in observed quantities we can calculated the mass function

$$f(M_2) \equiv \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{4\pi^2}{G} \frac{(a_1 \sin i)^3}{P_b^2} = \frac{K_1^3}{2\pi G} P_b.$$

for known sin I and $M_1 > 0$ this will be a lower limit on the compact star mass;

for a complete solution one needs the light curve as additional data

Best Black Hole X-ray Binaries

Binary	Likely $M_X(M_\odot)$	$f(M) \equiv M_{X,min}(M_\odot)$
4U1543-47	5 ± 2.5	0.22 ± 0.02
GRO J0422+32	10 ± 5	1.21 ± 0.06
GRO J1655-40	7 ± 1	2.73 ± 0.09
SAX J1819.3-2525	10.2 ± 1.5	2.74 ± 0.12
A0620-00	10 ± 5	2.91 ± 0.08
GRS 1124-683	7 ± 3	3.01 ± 0.15
GRS 1009-45	4.2 ± 0.6	3.17 ± 0.12
H1705-250	4.9 ± 1.3	4.86 ± 0.13
GS 2000+250	10 ± 4	4.97 ± 0.10
XTE J1118+480	7 ± 1	6.0 ± 0.3
GS 2023+338	12 ± 2	6.08 ± 0.06
XTE J1550-564	10.5 ± 1	6.86 ± 0.71
XTE J1859+226	10 ± 3	7.4 ± 1.1
GRS 1915+105	14 ± 4	9.5 ± 3.0

Figure 7: : **Black hole candidates.** Compact objects with a mass (M_X) greater than 3 $M\odot$, upper limit for a stable neutron star. Ramesh Narayan.

http://cgpg.gravity.psu.edu/events/conferences/Gravitation_Decennial/

“It is worth mentioning here that the accumulation of accreted material on the surface of a neutron star triggers thermonuclear bursts. These are called bursts of Type I.

No Type I burst has ever been observed from a compact object where optical observations resulted in a mass above 3 $M_\odot$.
That fact might confirm that in black holes there is no surface where material can accumulate “(Narayan & Heyl 2002).

<u>Observations of Type I bursts give a direct evidence for a neutron star</u>.

Compact Object Mass

Neutron Star Limit: 3 M

$(dP/d\rho)^{0.5} < c$

Rhoades & Ruffini 1974
Chitre & Hartle 1976
Kalogera & Baym 1996

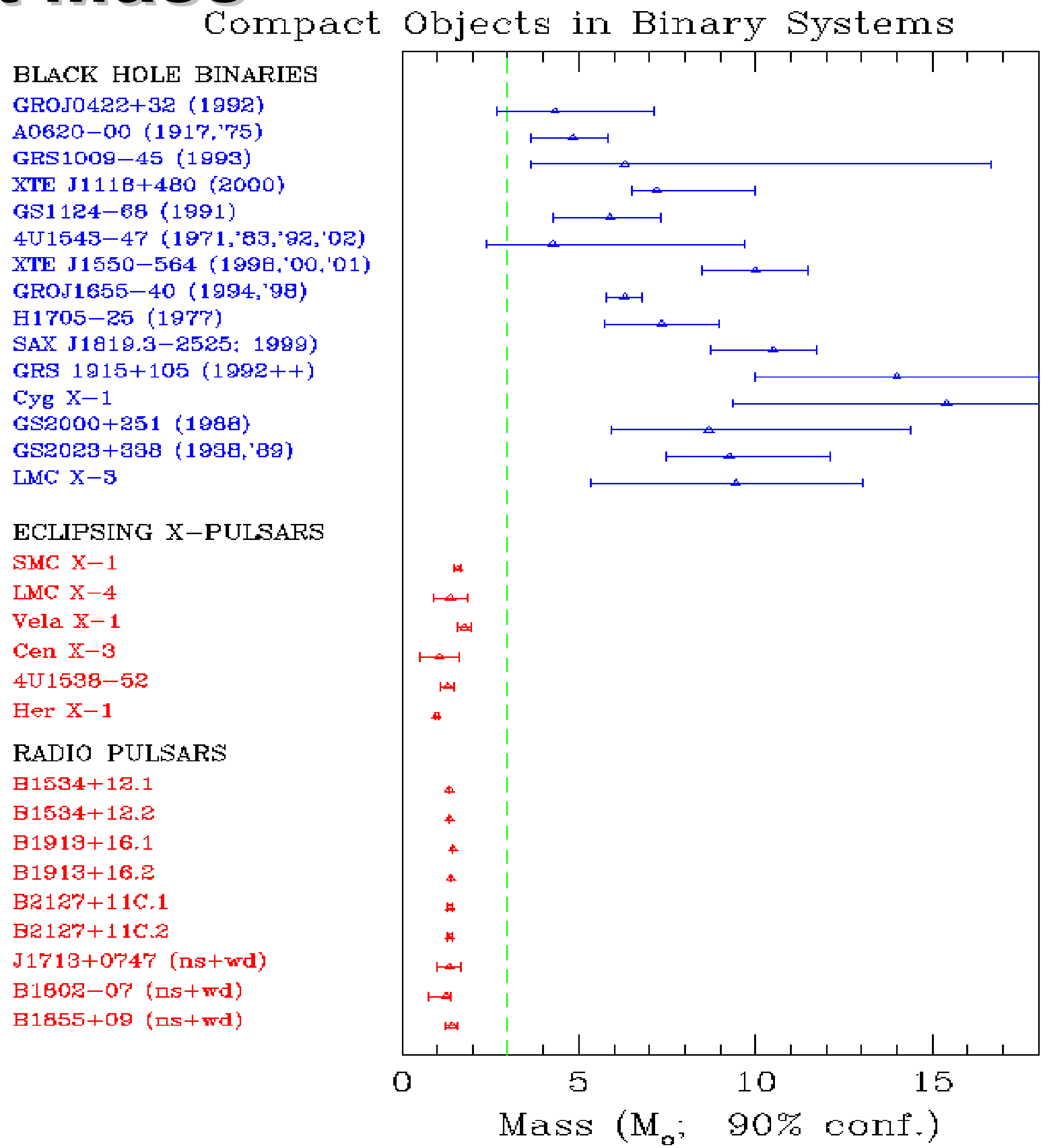
Black Holes (BH)

$M_x = 3\text{-}18\ M_o$

Neutron Stars (NS)

(X-ray & radio pulsars)

$M_x \sim 1.4\ M_o$



Demorest, P. B.; Pennucci, T.; Ransom, S. M.; Roberts, M. S. E.;
Hessels, J. W. T.

Nature, Volume 467, Issue 7319, pp. 1081-1083 (2010).

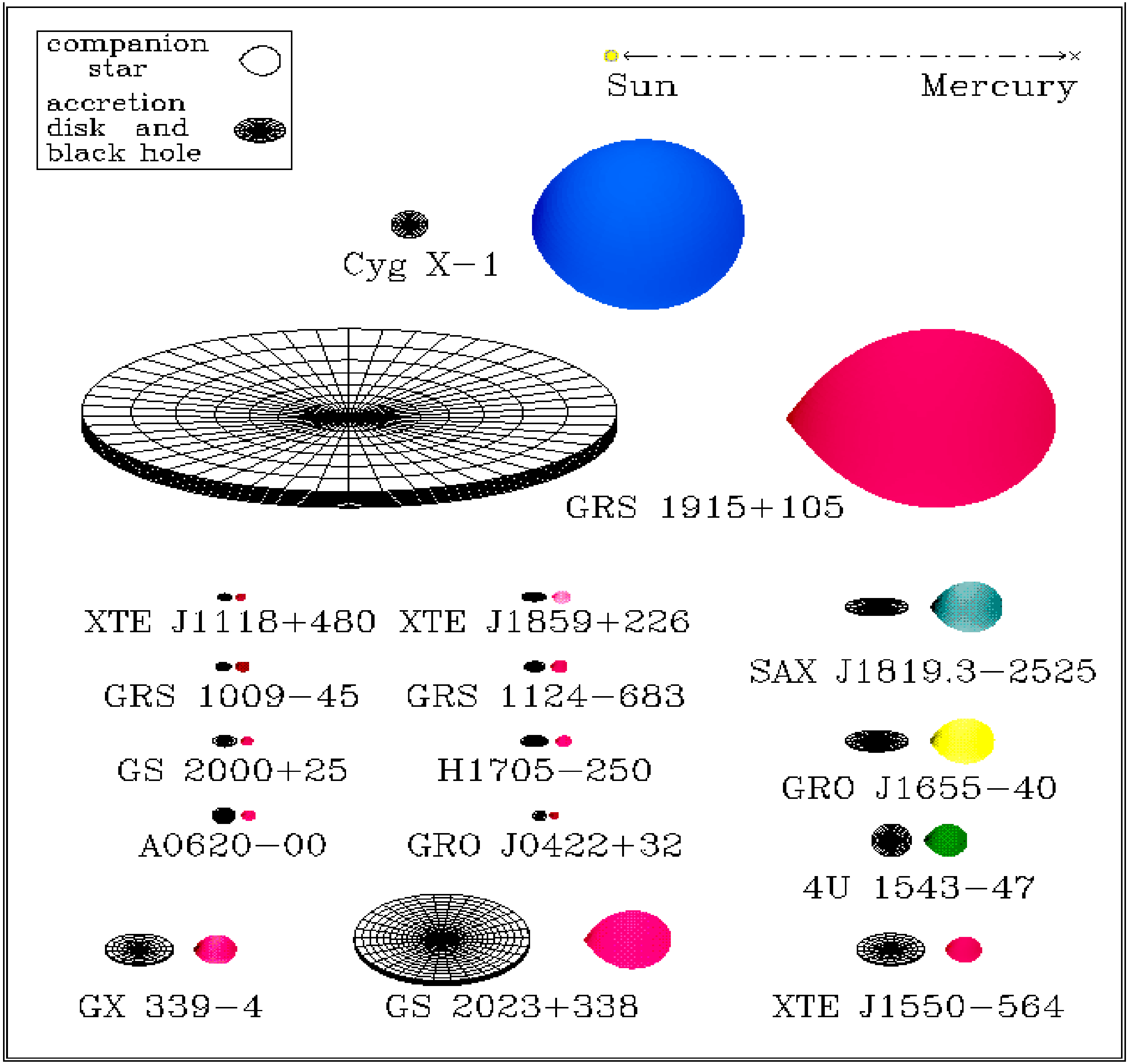
.... Here we present radio timing observations of the binary millisecond pulsar J1614-2230 ......**We calculate the pulsar mass to be (1.97+/-0.04) Msolar**

Inventory of Black Hole Binaries

BH Binary: Mass from binary analyses

	Dynamical BHBs
Milky Way	18
LMC	2
local group	1 (M33)
---------------------	---------------------
total	**21**

Transients 17



Black Holes in the Milky Way

Jerry Orosz