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 lines, one can determine the mass of the companion.
\[ p^2 = \frac{4\pi^2 (a_s + a_p)^3}{G(m_s + m_p)} \]
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: $4 \pi^2 (a_x + a_c)^3 = GP^2 (M_x + M_c)$

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”: $f(M) = PK^3 / 2\pi G = M_x \sin^3(i) / (1 + M_c/M_x)^2 < M_x$

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

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

\[ \frac{v_r}{c} \approx z \quad \text{if} \quad z << 1 \]
• 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

\[
\begin{align*}
    v_{1r}^{\text{max}} &= v_1 \sin i \\
    v_{2r}^{\text{max}} &= v_2 \sin i
\end{align*}
\]
Elliptical Orbits

\[ \text{eccentricity} = \frac{OF_1}{a} \]
Radial velocity shape as a function of eccentricity:
Eccentric orbit can sometimes escape detection: with poor sampling this star would be considered constant
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

\[ K_1 = \frac{2\pi a_1 \sin i}{P_b}. \]

using Kepler's laws
expressed in observed quantities we can calculated the mass function

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

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
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).

Observations of Type I bursts give a direct evidence for a neutron star.
Compact Object Mass

Neutron Star Limit: $3 \, M_\odot$
$$(dP/d\rho)^{0.5} < c$$
Rhoades & Ruffini 1974
Chitre & Hartle 1976
Kalogera & Baym 1996

Black Holes (BH)
$M_x = 3-18 \, M_\odot$

Neutron Stars (NS)
(X-ray & radio pulsars)
$M_x \sim 1.4 \, M_\odot$

Compact Objects in Binary Systems

BLACK HOLE BINARIES
GROJ1223+32 (1992)
A0620-00 (1917, 1975)
GRS1009-45 (1993)
XTE J1118+480 (2000)
GS1124-68 (1991)
H1705-26 (1977)
SAX J1819.3-2525; 1999
GRS 1915+105 (1992++)
Cyg X-1
GS2000+251 (1988)
LMC X-3

ECLIPSING X-PULSARS
SMC X-1
LMC X-4
Vela X-1
Cen X-3
4U1538-52
Her X-1

RADIO PULSARS
B1534+12.1
B1534+12.2
B1913+16.1
B1913+16.2
B3127+11C.1
B2127+11C.2
J1713+0747 (ns+wd)
B1602-07 (ns+wd)
B1855+09 (ns+wd)

Mass ($M_\odot$; 90% conf.)
Demorest, P. B.; Pennucci, T.; Ransom, S. M.; Roberts, M. S. E.; Hessels, J. W. T.


"...Here we present radio timing observations of the binary millisecond pulsar J1614-2230......We calculate the pulsar mass to be $(1.97+/-0.04)$ M$_{\odot}$"
### Inventory of Black Hole Binaries

**BH Binary:** Mass from binary analyses

<table>
<thead>
<tr>
<th>Dynamical BHBs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way</td>
<td>18</td>
</tr>
<tr>
<td>LMC</td>
<td>2</td>
</tr>
<tr>
<td>local group</td>
<td>1 (M33)</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>21</strong></td>
</tr>
</tbody>
</table>

**Transients** 17
Black Holes in the Milky Way

Jerry Orosz

18 BHBs in Milky Way

16 fairly well constrained

Scaled, tilted, and colored for surface temp. of companion star.

Cyg X–1

GRS 1915+105

XTE J1118+480  XTE J1859+226
GRS 1009–45   GRS 1124–683
GS 2000+25   H1705–250
A0620–00     GRO J0422+32

SAX J1819.3–2525
GRO J1655–40
4U 1543–47

GX 339–4
GS 2023+338
XTE J1550–564