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Black Holes in Binaries:

After the discovery of the pulsars, the identification of neutron stars and cataclysmic variables proceeded rather **quickly**. This was in part due to their spectra, luminosity and variability being in good agreement with theory. By comparison, the identification of black holes has been much more difficult. The main reason being that the distinction between black hole sources and other objects is based on what is "not" there. For example, the absence of a boundary layer might be an indication that the accretor has no hard surface. But, it could also be due to the fact that the disk is disrupted before it reaches the surface of the star.

Therefore, relying directly on the spectral information is not a reliable method of ascertaining whether a compact object is a black hole. Instead, the process of black hole identification has involved several observations that incorporate different types of analysis, to find a limit on the mass of the compact object.

We now know that X-ray binaries generally come in two varieties: the high mass (HMXB) and low mass (LMXB) sources. In the former, the companion is a supergiant O-B star. The latter typically have short orbital periods ($\lesssim 10$h) and low-mass companion stars. An important observational difference is that the optical flux in LMXB sources is triggered by reprocessing of the X-rays irradiating the accretion disk, whereas the supergiant companion dominates the optical spectrum in HMXB sources.

The strong evidence for the existence of black holes came from X-ray and optical observations of the high-mass X-ray binary Cygnus X-1. Early observations showed that the supergiant companion moves with a velocity $\gtrsim 75$ km s-1 in a 5.6 days orbit about an unseen companion. The projected orbital speed of the companion is given by:

$$v_c = \frac{2\pi}{T_{orb}} a_c \sin i$$

Here a_c is the distance of the companion from the center-of-mass of the system and i is the inclination angle. v_c can be determined from Doppler shift measurements. Since T_{orb} can also be found from variations in the companion's flux, one can the find $a_c \sin i$.

From the Kepler's laws we have:

$$\frac{G(M_c + M_X)}{a^3} = \left(\frac{2\pi}{T_{orb}}\right)^2$$

M_c: Companion's mass
M_X: Primary's mass

After some manipulation we arrive at the so-called "mass function":

$$f(M_c, M_X, i) \equiv \frac{(M_X \sin i)^3}{(M_c + M_X)^2} = \frac{v_c^3 \, T_{orb}}{2\pi G}$$

Since the right-hand side can be found from observations, the mass function is a measurable quantity. An important property of it is that $f \leq M_X$. Therefore the mass function provides an absolute lower bound on M_X. Additional information on M_c and $\sin i$ can strengthen this bound.

In the case of Cygnus X-1, one knows that $M_c \gtrsim 8.5 M_\odot$ from the supergiant luminosity and its distance (~ 2.5 kpc) from Earth. Based on the absence of X-ray eclipses, one can also find an upper limit of $i \lesssim 60°$ on the inclination angle. A very reliable lower limit can then be inferred on M_X:

$M_X \gtrsim 4\, M_\odot$

The significance of this result rests on the fact that a neutron star cannot support itself against gravitational collapse for arbitrary large masses. The Chandresekhar limit ($\simeq 1.44\, M_\odot$) is obtained for a degenerate gas of non-interacting particles. It is conceivable that larger masses may be supported by harder equations of state that arise at very high densities. However, if general relativity is correct, this lack of precise knowledge about the equation of state can be surpassed by a causality argument. When the speed of sound c_s exceeds c (which happens as the star becomes more compact), different parts of the star could no longer communicate in causal manner, and gravitational infall will become inevitable. Original calculations, and more recent simulations, suggest that this happens at a mass $\sim 3 M_\odot$. This is the maximum neutron star mass that allows a stable configuration.

Cygnus X-1 was soon joined by a new X-ray object, A0620-00, which is an X-ray nova associated with a LMXB source. The companion star is moving at 457 $km s^{-1}$ with an orbital period of 7.8 h. The mass function for this system is therefore $f = (3.2 \pm 0.2) M_\odot$. Conservative estimates place the companion mass at $\sim 0.25 M_\odot$, and since there are no X-ray eclipses in this system, the inclination angle is inferred to be $i < 85°$. The mass of the compact object is therefore found to be:

$M_X \gtrsim 3.2 \; M_\odot$

A little over a decade late another X-ray transient, named V404 Cyg, was found. Spectroscopic analysis of this new system revealed a velecity of 211 $km s^{-1}$ in a 6.5 day orbit for the companion. The mass function is therefore $f = (6.3 \pm 0.3) M_\odot$.
As a result, one finds;

$M_X \gtrsim 6 \; M_\odot$

This is independent from M_c and i. It is well above the neutron star limit of $\sim 3 \; M_\odot$, which can be considered as a proof of stellar sized black holes. Many other black hole binaries have been discovered in which the mass function is in the excess of $5 \; M_\odot$.

There currently exists a catalog of 20 black hole binaries that are confirmed on the basis of dynamical arguments. The vast majority of these are transients, and only three (Cygnus X-1, LMC X-1, LMC X-3) are persistent sources.

Additional support for black hole identification of these sources is provided by observations that focus on their spectral and timing characteristics. For example, luminosity of V404 Cyg is saturated at $L_X \sim 10^{39}$ erg s^{-1}, which implies probable witnessing of the maximum possible X-ray power radiated at the Eddington limit:

$$L_{edd} \simeq 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{erg } s^{-1}$$

This means an accretor mass of $M_X \sim (7-8)\, M_\odot$. Other features in the spectrum or light curve that may be used to support the black hole nature include the following:

1- The absence of a boundary layer.

2- The absence of pulsations or X-ray bursts.

3- Faintness of the binary system. Matter flowing through the event horizon of a black hole advects a fraction of the dissipated gravitational energy with it. Thus, on average, the black hole binaries are expected to be dimmer than their neutron star counterparts. Observationally, black hole systems are seen to be ~100 times fainter than quiescent neutron star binaries with the same orbital period.

Finally, let us emphasize that the mentioned collection of stellar-sized black holes is a tiny sample of what is believed to be the complete galactic population. Dynamical studies of X-ray transients reveal that roughly $\frac{3}{4}$ contain a black hole. An extrapolation of the number of these sources suggests that there is a dormant population of at least 1000 or so such systems. From a theoretical standpoint, we expect a much bigger number than this. Stellar evolution models predict a population closer to 10^9 stellar-sized black holes in the galaxy.