Lec 30: 12/01/2014

Black Holes in Binaries:

After the discovery of pulsars, the identification of neutron stars and cataclysmic variables proceeded rather quickly. This was in part due to their spectra, lumionsity, and variability being in good agreement with theory. By comparison, the identification of black holes has been much more difficult. The main reason ~~is~~ that the distinction between black hole sources and other objects is based on what is "not" there. 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 and low mass sources. In the former, the companion is a supergiant O-B star. The latter typically have short orbital periods ($P_{orb} \lesssim 10$ h) and low-mass companion stars. An important observational difference is that the optical flux in low-mass sources is triggered by reprocessing the X-rays irradiating the accretion disk, whereas the supergiant companion dominates the optical spectrum in high-mass sources. The strong evidence for the existence of black holes came from X-ray and optical observations of the high-mass binary Cygnus X-1. Early observations showed that the supergiant companion moves with a speed $\approx 75\,kms^{-1}$ in a 5.6 days orbit about an unseen compact object. The projected orbital speed of the companion is given by:

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

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 P_{orb} can be found from variations in the companion's flux, one can the find $a_c \sin i$. From the Kepler's law, we have:

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

Here M_c is the companion's mass, M_X is the mass of the compact object, and "a" is the distance between the primary and the companion. After some manipulations, we arrive at the so-called "mass function" relation:

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

Since the right-hand side can be found from observations, the mass function "f" is a measurable quantity. An important property of it is that $f \leq M_X$. It therefore provides an absolute lower bound on M_X, which can be strengthened with additional information on M_c and $\sin i$.

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 the 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 on M_X can the be inferred:

$M_X \gtrsim 4 M_\odot$

The significance of this results rests on the fact that a neutron star cannot support itself against gravitational collapse for arbitrarily large masses. The Chandraselchar 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 a harder equation of state arising at very high densities. However, within the framework of general relativity, the lack of precise knowledge about the equation of state can be surpassed by a causality argument. As the mass increases, a harder equation of state is needed in order to keep it stable. However, C_s (speed of sound) increases when the equation of state becomes harder, but it cannot exceed the speed of light "c". 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 low-mass source. The companion star is moving at $457\ km\,s^{-1}$ with an orbital period of 7.8 h in this case. The mass function for this system is therefore $f \simeq 3.2\ M_\odot$. 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 later, another X-ray transient named V404 Cyg was found. Spectroscopic analysis of this new system revealed a velocity of 211 $km s^{-1}$ in a 6.5 days orbit for the companion, which results in $f \simeq 6.3\ M_\odot$. As a result, one finds:

$M_X \gtrsim 6\ M_\odot$

This 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 since then in which $f > 5\ M_\odot$.

Additional support for black hole identification 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 $M_X \sim (7\text{-}8) M_\odot$. Other features in the spectrum or light curve that may be used to support the black hole nature include the absence of a boundary layer, and the absence of pulsation or X-ray bursts. These are due to the fact that black holes do not have a hard surface. Also, matter flowing through the horizon of a black hole advects a fraction of 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 that are ~100 times fainter than quiescent neutron star binaries with the same P_{orb}.

Cygnus X-1 as the Archetypal High-Mass Sources:

Since its discovery, Cygnus X-1 has been closely monitored by many high energy instruments from X-rays to γ-rays. Its spectrum has been known for decades to be a mixture of thermal and non-thermal components. The thermal component may be modeled as a multi-temperature blackbody with a flat segment that originates from the accretion disk. The non-thermal component is modeled as a power-law originating from the particle distribution with a spectral index of ~2. The power law

extends to much higher energies than the thermal component, which falls off exponentially beyond ~100 keV.
Cygnus X-1 is most often found in the low hard state (LHS), defined by a relatively low flux in soft X-rays (~1 keV) and a high flux in hard X-rays (~100 keV). Occasionally, it switches to the high soft state (HSS), in which the high-energy power law is much softer (index of ~2.4).
Sometimes, it is detected in an intermediate state (IMS), which is a transitory configuration exhibiting a relatively soft X-ray spectrum (with spectral index ~2.1-2.3), and a moderately strong soft thermal component.
Simultaneous observations of Cygnus X-1 in the radia and X-ray bands have revealed that during the LHS strong radio emission arises from a jet-like feature extending

out from a core. In contrast, the jet is rather weak during the HSS. The fact that the radio jet is present in the LHS and not the HSS is an indication that transitions from one state to the other must be associated with significant change in the geometry of the accretion flow.

It is believed that a transition from the HSS to the LHS is associated with the truncation of the disk at several hundred Schwarzschild radii. A geometrically thick, optically thin, hot disk forms between the truncation radius and the event horizon. A switching back to the HSS results when the hot gas cools and collapses back down toward the plane and the cold disk refills its inner region.

An important **observation** is a rather broad feautre around ~500keV, which is due to electron-positron pair annihilation.

Also, at least 80% of the radio jet in the LHS is composed of electron-positron pairs. Together, these suggest that the compact object is disgorging an intense flux of high-velocity electron-positron pairs into the surrounding medium. Production of these pairs requires temperatures that exceed the electron mass ($\sim 10^{10}$ K).

- As discussed earlier, thermal instabities in the accretion disk arise in the range $10^5\,K \lesssim T \lesssim 10^8\,K$, which can give rise to the formation of a geometrically thick disk in the inner regions. Observed features in the spectrum of Cygnus X-1 may be explained by models that take these instabilities into account.

X-ray Nova:

There ~~is a large number of~~ catalogued X-ray binaries in the galaxy each containing a neutron star or a black hole accreting from a companion. The great majority of these are persistent sources, and about 30 or so are transients with nova-like outbursts, which occur from once every several years to perhaps one per century (or longer).

Almost all of the black hole binaries are X-ray nova, which are characterized by episodic outbursts at X-ray, optical, and radio frequencies. Conventional wisdom is that the outburst is caused by a sudden dramatic increase in the accretion rate through the disk. In these systems, the mass transfer from the companion fills the outer region of the disk in order to sustain a continuous viscous flow in steady state. At some point, a critical condition that triggers an outburst is met. This has probably something to do with the strong temperature dependence of the viscosity and thermal instability, which was mentioned before. The X-ray flux rises on a timescale of several days, and subsequently declines over a period of weeks to months. During outbursts, the X-ray flux may be several million times larger than its value during quiescence. A well-known member of this group is the X-ray nova GRS 1124-684. Observations of this source during the flare demonstrates the emergence of an electron-positron annihilation line in the 430-530 keV band. This also indicates a big rise in the temperature to kinematically allow electron-positron pair production from photon interactions.