VARIABLE X-RAY SOURCES AND BLACK HOLES IN BINARIES

(Joint Discussion of Commissions 27, 35, 40, 42 and 48)

Fourteen speakers participated in this discussion, which lasted the whole day of 23rd August 1973. The morning was devoted to the X-ray and optical observations while the theoretical models and radio observations were considered in the afternoon.

The joint discussion was opened by a survey talk on X-ray observations of binaries by Tananbaum. He started by pointing out that out of the 44 X-ray sources with luminosity greater than 35 counts, as many as 38 are found to be variable, and among them 6 are known binaries while 9 other candidates are under study. Then he considered some of the individual sources.

Hercules X-1 is the best studied object which contains a rotating neutron star as one member of the binary system. The period is 1.70017 days and the duration of the eclipse is 0.24 day. Optical variation is in phase with the X-ray variation, but the duration of the eclipse is longer. The neutron star exhibits a pulse of $1^{s}.2378206$ period which shows the Doppler shift pattern with maximum delays of $\pm\ 13^{s}.2$ giving $a \sin i = 3.95 \times 10^{11}$ cm and $f\,(M) = 1.69 \times 10^{33}$ gm. The pulsation period shows increase and decrease of 3 to 6 microseconds, which might be caused by the accretion of matter coming from the primary. This matter may form a disk and then fall on the neutron star, thus increasing its angular momentum. The X-ray luminosity of 10^{36} ergs/sec is consistent with this picture. Combining the X-ray observations with the spectroscopic and photometric data, one can determine the mass by assuming the radius of the larger star to be equal to the radius of the Roche lobe. On varying the assumed value of i from 90^0 to 60^0, the mass of the neutron star is found to range from 1.19 to 0.09 $M_\odot$ while that of the companion has the range of 2.09 to 1.47 $M_\odot$. Her X-1 also shows a slow variation with a period of about 35 days, the turn-on occuring at optical phases 0.2 to 0.3 and 0.65 to 0.70. It is attributed to the precession of the neutron star. Triggering of X-ray activity might occur when one or the other pole is turned toward the inner Lagrangian point L_1.

Centaurus X-3 pulses with a period of $4^{s}.842$, which shows Doppler shift pattern as well as occultation. Irregular variations with a larger period of months may be present. Reduction in period of 4 milliseconds is observed. The orbital period of 2 days also shows changes indicating loss of mass of the order of $10^{-5}\ M_\odot$/yr. Optical counterpart of 14^{m} may be present (see later discussion).

Other binary sources are: 3U 1700-37, 2U 0900-40, SMC X-1 (2U 0115-73), HD 253919 and HD 77581. Sco X-1 shows 5 per cent variation in one second; optical observations may help in deciding whether it is a binary.

Parkinson reported observations of Cen X-3 at 42 keV with Copernicus satellite; he found a period of 119 minutes and a position at $11^{h}\,18^{m}$, $-60^{0}19'.5$.

Boyd described observations of four sources in the ranges 1-3 Å, 3-9 Å and 6-18 Å. Cyg X-3 has a period of $4.792 \pm .001$ hrs, its light curve varies from cycle to cycle and is asymmetric, and X-ray variation is correlated with the 2.2 micron infrared variation. In Her X-1, he found significant flux during off periods. Cir X-1 has an off period and it is suspected to be an eclipsing binary. Cyg X-1 has the least photon count at the central point; it has a period of 5.5960 days and turn-off occurs when the optical counterpart (HD 226868) is moving away. It appears to be a binary, perhaps with a black hole.

Peterson reported hard X-ray observations of X-ray binaries in the 7 to 100 keV range. Her X-1 has dips which coincide with the low energy data, shows cut-off at 35 keV and a black body temperature of 6×10^{7} °K outside eclipse. Vela X-1 also shows dips corresponding to UHURU data; there are fluctuations outside eclipse and cut-off occurs at 50 keV. Cyg X-1 shows no eclipse; its spectrum, which is flatter for $E > 30$ KeV and steeper for $E < 30$ keV, resembles the Bremsstrahlung spectrum of 65 keV. Cyg X-3 is similar to Cyg X-1, but a sine variation in phase with the UHURU period of 4.8 hrs is seen with an amplitude equal to 0.22 ± 0.19 of the average luminosity. SMC X-1 has a spectrum with slope —1 and cut-off at 30-35 keV. Cen X-3 has a spectrum with the steep slope of —2.96, quite unlike other sources.

Optical data on 5 X-ray binaries were discussed by Hutchings. All have short periods of a few days with ellipsoidal light variation. Light curves, when combined with radial velocity observations, would give masses of collapsed objects. Models of the systems with one luminous component and an invisible companion can be obtained by comparing the predicted and observed light curves under various assumptions regarding the ratio of the radius of the larger star to the Roche radius, mass ratio Q, surface temperature, etc. Complications could arise from noncircularity of the orbit and the heating caused by the X-ray source. For many systems, nonzero eccentricities upto 0.2 are found. Masses of 1.3 to 2.4 $M_\odot$ are found for the compact components which correspond to neutron stars. In the case of Cyg X-1, a value of $i=27°$ gives $Q=1.6$ and M (secondary) $=14\ M_\odot$, which might therefore be a black hole.

Garrison suggested that CD-33°12119 may be a possible candidate for the optical indentification of the X-ray source GX 354+0. It is an extremely red object with an image tube spectrum of A supergiant, showing P-Cygni type hydrogen line profiles. Although $V=10.20$ is nonvariable, $B—V=2.10$ and $U—B=1.20$ are found to vary by 0.1 and 0.3 magnitude, respectively, in times of the order of minutes.

Kemp measured Zeemann effect (from differential circular polarization) and linear polarization in the Balmer lines of 3 X-ray sources: HD 77581, θ^2Ori and HD 153919 as well as in Beta Lyrae and HD 226868 (Cyg X-1). Variations of circular polarization in phase with the orbital period were found. This is to be expected if the magnetic field of the visible component is locked to the neutron star for avoiding entanglement of the lines of force of both the stars. Variation of linear polarization was also noted, indicating alternate clockwise and anti-clockwise rotation as one or the other pole is pointed toward the observer.

Vidal discussed optical observations of three stars. Fortythree visual observations of HD 77581 on 34 nights showed a total variation of 0.1 mag with a period of 8.95 days (same as X-ray period); radial velocity data indicated gas streams near conjunction. The secondary may be a black hole as its mass appears to lie between 2 and 3.5 $M_\odot$. No star of $m_V < 14$ is a possible candidate for Cen X-3; this leads to a mass greater than 3 $M_\odot$ for the invisible component, making it a possible candidate for a black hole.

Rees gave a brilliant review of the theoretical aspects of X-ray binaries. The X-ray source in the binary is a compact object which could be a white dwarf, a neutron star or a black hole. If the mass is transferred from the larger star through the inner Lagrangian point L_1 and falls on the neutron star, then 1-10 per cent of its rest mass energy can be released. The energy released by accretion onto a black hole can be as high as 40 per cent if the black hole is rotating. The energy ($\sim 10^{38}$ ergs will be radiated largely in the X-ray region.

If the central object is a spinning magnetic neutron star like a pulsar, we need 10^6 times more energy than a pulsar, which in this case comes from the accreted matter. If we assume an oblique rotator, its magnetic field will be limited by the Alfven radius inside which the matter will flow along magnetic lines of force and thus get funnelled towards the poles. Radiation can be produced either by Bremsstrahlung or by cyclotron process. The spin of the neutron star will produce pulses, their shape and polarization being determined by the beam pattern. The 35 day period of Her X-1 can be explained if we could find a mechanism for switching off the X-rays. Possible mechanisms are: (*i*) Switching off of mass transfer by the pulsation of the primary causing a filling of the Roche lobe at certain times only; (*ii*) A negative feed-back in which X-ray radiation pressure obstructs mass flow; (*iii*) A positive feed-back in which strong overflow of matter stops X-rays by increasing optical depth; (*iv*) Precession of the neutron star with a solid core. The theoretical upper limit of neutron star masses is about 2 $M_\odot$, which is satisfied by most X-ray binaries.

If the compact object is a black hole, it can still accrete material, but it has no hard surface and no magnetic field. The limit of the black hole is determined by the circular orbit of the least angular momentum. The binding energy for this orbit can be as high as 42 per cent of the rest mass energy for Kerr metric describing a rotating black hole. Most of the energy is released within a few Schwarzschild radii ($R_S = 3 \times 10^5$ $M/M_\odot$ cm). The characteristic signature of X-ray produced in this case would be the absence of a definite period and irregular flickering of time scales upto millisecond. For real identification, the mass should be high. This seems to be the case for Cyg X-1 and perhaps for SMC X-1.

Some of the outstanding questions are: Why is the 35-day cycle of Her X-1 not seen in the optical region? How do these systems evolve? How did the accompanying supernova explosion go unnoticed? What about sources like Sco X-1?

Rees' paper was followed by several short discussions. Meyer observed that the Roche lobe of the primary of Her X-1 is not filled because the observed mass transfer rate of $10^{-9} M_\odot$ /yr is much smaller than the estimated rate of $10^{-6} M_\odot$/yr for a filled Roche lobe. Wade described the interferometric observations of radio binaries made by Hjellming at 8085 MHz and 2695 MHz. For the novae HR Del (1967), FH Ser (1970) and V 365 Sct (1970), the radiation is found to be consistent with an expanding plasma. In the ordinary radio binaries: α Sco B, β Per, β Lyr, b Per and AR Lac, the periods are found to change slowly or in jumps. These stars also show flare activity. The strongest radio emission is found in β Per in which the major flare has no correlation with optical variation. It can be interpreted as plasma radiation of 10^6 °K. Miley observed Sco X-1 at 6 cm and 50 cm; he found that it varies in the radio region as in X-ray and optical regions.

R. E. Wilson considered the possibility whether the invisible component of β Lyr is a black hole. It is definitely more massive with Q=4 to 6. But it is a composite source consisting of high and low temperature regions. If we assume a thick flattened disk as postulated by Huang, it could be approximated by a highly elongated ellipsoid with the axes ratio of 1 : 3. Then the poles will be 2500° to 3000° K hotter than the equatorial regions; since we do not see the poles, the star will appear underluminous by as much as 1 magnitude. Further, the lines will be washed out by rotation. Hence the secondary appears underluminous and it may not be a black hole.

The discussion ended with a paper by Kondo in which he considered the problem of mass determination of close binary stars, particularly X-ray sources. He drew attention to the effect of radiation pressure on the size of the Roche lobes and mass-luminosity law for evolved stars in binaries.

K. D. Abhyankar

Astronomy Department
Osmania University
Hyderabad 500 007