Some aspects of evolution and mass transfer in X-ray binaries

Savonije, G.J.

Publication date
1977

<u>Preface</u>

The first galactic X-ray sources outside the solar system were discovered in 1962 with a rocket experiment (Giacconi et al. 1962). Since the launching of the first X-ray satellite at the end of 1970 new discoveries were made almost dayly and a wealth of observational material has been accumulated. From the beginning on, an association was suggested between the galactic X-ray sources and the supernova phenomenon, one of the most energetic processes in a galaxy. When a star at the end of its nuclear evolution is more massive than the Chandrasekhar limiting mass ($\sim 1.4\ M_\odot$), a supernova event seems inevitable. Due to the high central temperatures and resulting photodisintegration of even the most stable nuclei (Fe^{56}) in the stellar core, obviously a highly endothermic process, the iron core collapses under its own gravity to densities of nuclear matter - or even higher, releasing a strong neutrino flux. If the core collapse can be halted by the pressure of the degenerate neutron gas - which is produced by inverse β-decay of the protons liberated by the photo-disintegration a new stable configuration arises in the form of a neutron star. The existence of neutron stars was predicted theoretically by Landau (1938). The first models of neutron stars were calculated by Oppenheimer and Volkoff (1939). These predictions were beautifully confirmed by the discovery of the radio pulsars in 1967. These objects show very regularly pulsed radio emission and are identified with the rapidly rotating magnetic neutron star remnants of supernovae. A key role in this discovery was played by the two youngest of the approximately 150 discovered radio pulsars, the Crab and Vela pulsars, which both are located at the centers of recent, nearby supernova remnants. Supernova remnants are one class of galactic X-ray sources, but there is at least one other class of these objects. During the last 6 years it has been firmly established by a combination of X-ray observations from space and ground-based optical observations that certainly a dozen of the about 150 galactic X-ray sources is situated in close binary systems. The binary character is - in most cases - established by the occurence of regular X-ray eclipses or by regular optical variations. It seems likely - from statistical considerations - that the majority of the strong galactic X-ray sources are binaries, but have not yet been identified as such. The short time variability - down to timescales of seconds or even milliseconds - shown by these binary X-ray sources indicates a very small size of the X-ray emitting region. A currently accepted model for this class of X-ray sources consists of a gravitationally bound double star of which one member is an extremely condensed star, i.e., a neutron star or black hole. Several of these binary X-ray sources show regular X-ray pulsations with periods of the order of seconds, indeed suggesting them to be rotating neutron stars. The compact star forms a very deep gravitational well - for a neutron star the surface gravitational potential typically amounts to 0.1 c^2. Hence, when the other (normal) member of the binary system transfers matter to its compact companion, the infalling matter gains an amount of kinetic energy equivalent to some 10% of its rest mass before it reaches the neutron star surface. Obviously, accretion by such a collapsed object is a very efficient way of energy liberation. For comparison, the total energy liberated by nuclear reactions during a stellar lifetime amounts to less than 0.7% of the rest mass of the fuel. Bright X-ray binaries have typical X-ray luminosities of about 10^{37} ergs/sec, requiring accretion rates of the order of 10^{-9} $M_{\odot}$/yr, which seems quite reasonable.

The infalling plasma most likely originates from the normal companion of the neutron star and is transferred either by a stellar wind or by Roche-lobe overflow (Davidson and Ostriker 1973). Stellar wind is a type of mass loss that occurs in the form of a highly supersonic, essentially isotropic, outflow of matter from the stellar atmosphere. This type of mass loss is independent of the binary character and would also occur if the star were single. Since only a very small fraction (10^{-3}) of the wind matter is gravitationally captured by the neutron star, the normal companion must lose some 10^{-6} $M_{\odot}$/yr in order to power a bright X-ray source. Only massive supergiants and Of-stars are believed to have such dense stellar winds.

Roche-lobe overflow, the alternative mass transfer mechanism, occurs only in binary systems and can give rise to much higher accretion rates. Roche-lobe overflow takes place if the relatively unevolved companion expands (due to its nuclear evolution) beyond the gravitational saddle point in between the two binary components. The outer layers of the expanding star are then captured by the strong gravitational field of the neutron star.

The discovery of the binary X-ray sources has triggered much fundamental work on the physics of accretion processes onto compact objects. The dynamics of the infalling plasma is dominated by the huge magnetic field of the neutron star as soon as it reaches the so called Alfvén surface, defined by the balance between the ram pressure of the infalling plasma and the magnetic pressure of the stellar field. The Alfvén surface is situated at a typical distance of some 10^8 cm from the stellar centre, i.e., at 10^2 times the star's radius.

The stellar magnetic field is usually assumed to be (essentially) dipolar and to have a surface strength of the order of 10^{12}-10^{13} gauss (Ruderman 1972). This seems to be confirmed by recent X-ray spectroscopic observations (Trümper et al. 1977).

The strong magnetic field induces currents in the infalling plasma that effectively screen this stellar field outside the Alfvén surface (Lamb et al. 1973). In the magnetosphere (the region inside the Alfvén surface which is corotating with the neutron star) the plasma flow is directed primarily along the magnetic field lines, so that it can reach the neutron star surface only near the magnetic poles.

We may expect that our knowledge about these accretion processes will grow rapidly in the next few years, as this field is in rapid progress. Preliminary calculations by Lamb et al. (1973) indicate the formation of a hot ($\sim 10^8$ K) X-ray emitting accretion region near the magnetic poles, having an area of only ~ 1 km^2. The pulsed character of the X-ray emission can be explained by the non-alignment of the neutron star magnetic and spin axes.