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MASS FLOW IN AND OUT OF CLOSE BINARIES

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RESUMEN

Se discute el flujo de masa en estrellas binarias interactuantes, incluyendo las que contienen objetos colapsados, tanto en términos de datos provenientes de la observación como desde una base teórica. La noción de flujo de masa enteramente conservativo surge del modelo de desborde del llamado "lóbulo de Roche" según el cual la masa perdida por una componente es incorporada por la estrella compañera. Si se examina críticamente el problema restringido de tres cuerpos, se puede mostrar que esta conjetura es inválida. Observaciones reales realizadas en numerosas binarias, en varios rangos de longitud de onda, incluyendo el ultravioleta, muestran una compleja dinámica del gas, que incluye corrientes gaseosas dentro y fuera de la binaria, probables discos de acreción en algunos sistemas y acreción sobre la compañera.

ABSTRACT

Mass flow in interacting binary stars, including those with collapsed objects, is discussed in terms of both observational data and theoretical basis. The notion of wholly conservative mass flow arises from the so-called "Roche lobe" overflow model, in which the mass lost from one component is accreted by its companion star. This conjecture can be shown to be invalid when the restricted three-body problem is examined critically. Actual observations made in a number of binaries in several wavelengths, including the ultraviolet region, show complex gas dynamics, involving gas streams within and out of the binary, putative accretion disks in some systems, and accretion to the companion.

Key words: **BINARIES: CLOSE — STARS: MASS LOSS**

1. CRITICAL EQUIPOTENTIAL SURFACE OR THE "ROCHE LOBE"

The concept of the critical equipotential surface, which is popularly known as the 'Roche lobe', is often misunderstood and is, in consequence, applied incorrectly.

This equipotential surface arises from the solution of the restricted three-body problem. It describes the gravitational field experienced by a mass-less body in the vicinity of two point masses orbiting each other in a perfect circle, in the absence of any other force such as radiation pressure or stellar wind. If the restricted three-body conditions are not met, the surface does not exist mathematically. These solutions do not apply to binaries with orbital eccentricities. As Zdenek Kopal once pointed out, if there is an eccentricity in the orbit, the Roche equipotential surfaces do not exist. Since there are probably no binaries with mathematically perfect circular orbits, the restricted three-body solutions are at best approximations for real binaries.

Because of the use of the term Roche 'lobe', however, there are those who have the mental picture that gaseous particles within are contained physically inside the 'lobe' and can exit only through the gravitationally neutral inner-Lagrangian point. The choice of the term 'lobe' has been rather unfortunate as it apparently conjures up an image of a container whose surface is impenetrable. The Earth, for instance, has an infinite number of equipotential surfaces; yet, air carries molecules through those surfaces freely.

In the presence of radiation pressure, the equipotential surfaces are modified significantly, cf., Schuerman (1972), McCluskey & Kondo (1976), Sahade & Wood (1978), Zorec & Niemela (1980a,b). In early type stars, the use of the Roche lobe is entirely untenable. Heating at the stellar surface can also propel gaseous streams

(Modisette & Kondo 1980); the flow will be controlled by the dynamics of the wind modified by the gravitational forces of the two stars.

Even if all the conditions of the restricted three-body problem were met, unless the evolving star matched the shape of a tear-drop shape of the Roche lobe, the gas would not have access to the inner-Lagrangian point before it grew beyond the critical Roche surface. (Any asynchronous rotation of a star would prevent the star from conforming to a tear-drop shape). By the time the part of the star facing its companion reaches the L_1 point, the rest of its surface will have grown beyond the Roche surface. The protruding atmosphere will then have access to the region surrounding both stars. The excess gas can engulf both stars and present the appearance of a contact binary.

The concept of the so-called "Roche lobe overflow" would not be tenable even if it were stipulated, against all physical considerations discussed above, that the outer atmospheres of the evolving star would completely fill the critical equipotential surface as it expanded. Let us further stipulate that the gas would first start to leak out through the inner Lagrangian point toward its companion. If the gas were flowing out at a rate commensurate with the evolutionary processes in the binary —say, something on the order of 10^{-4} to 10^{-6} solar mass per annum— the velocity of that gas stream would have to be at least several hundred kilometers per second. (How else could you transfer that much mass in so short a time scale?) Remember also that we are talking about compressible gas. The gas stream could not and would not follow the contours of any Roche equipotential surface; it would rapidly overflow it. If the gas were not flowing at such a fast rate, the expanding atmosphere of the evolving star would become greater than the critical surface without the leak through the L_1 point playing a predominant role as would be expected in the conventional "Roche lobe overflow" model.

One might ask then whether the concept of the critical Roche equipotential surface has any usefulness in understanding the evolutionary processes in close binary stars. The answer is actually "Yes!". It defines an approximate boundary within which the atmosphere of the evolving star can expand while still remaining a distinctly separate object. If that rough boundary is exceeded, the expanding atmosphere will have access to the domain containing both stars. One will not encounter two distinctly separate stars in a binary, where one of them is clearly greater than its critical Roche equipotential surface.

2. CONSERVATIVE VERSUS NON-CONSERVATIVE MASS FLOW

The idea of wholly conservative mass flow has its origins in the idea of the so-called "Roche lobe overflow" model. In this model, a more massive component evolves and fills its 'Roche lobe' entirely. At this point, the expanding atmosphere escapes from that star only through the inner-Lagrangian point and the outflowing gas is accreted entirely by the companion without any loss to the binary system. In one version of this scenario, this process repeats itself as the companion, which sometimes becomes the more massive of the two, evolves to fill its 'Roche lobe' and throws back its expanding atmosphere to the star that originally lost the mass. The process could repeat itself thereafter. Naturally, the configuration of the 'Roche lobe' will keep changing as the masses of the components change back and forth.

The problem with this scenario is that it totally ignores the mechanics of the restricted three-body problem. It also treats mass flow as free particle trajectories when it really is a hydrodynamical problem, or more accurately, a magneto-hydrodynamic one. Simply put, there is no theoretical basis to believe that mass flow in close binaries is fully conservative.

Actual mass flow will be controlled by a number of factors, including mechanics, magneto-hydrodynamics, radiation pressure and others. It is perhaps of interest to note that the earlier papers by Struve (1941) and Kuiper (1941) showed remarkable insight into the complexity of mass flow phenomena in contrast to the notions held by the latter-day advocates of the 'conservative mass exchange' idea.

Actual observations of the gas flow in selected bright close binaries show complex patterns, as will be discussed at the end of this paper.

3. ACCRETION PHENOMENA

Even though the fully conservative mass flow model is invalid, physics does not prohibit the accretion of some of the out-flowing matter (from the evolving star) by its companion. Such accretion may take place directly; or, the gas may first form an orbiting, amorphous gaseous ring (or rings) —often called accretion disk— and then be accreted by the companion star.

The choice of the term 'accretion disk' is somewhat unfortunate as it tends to evoke a mental image of a flat and thin disk-like structure. The term 'ring' is somewhat better as it imputes some thickness, although an accretion ring is bound to be amorphous and irregular in appearance. Speaking of 'accretion disk' there even were papers, in which some astronomers discussed the precession of the accretion disk in HZ Her (Her X-1) treating the disk as though it had been a solid body; see Kondo, Van Flandern, & Wolff (1983) for a fuller discussion.

If the orbital period is short, say a few days, the separation of the two stars is not sufficient to permit the formation of a disk. Of course, this rule about the short period does not necessarily apply to binaries with compact objects, say, white dwarfs or neutron stars. In U Cephei, with a period of about 2.5 days, a part of the outflowing mass is accreted directly, and the rest flows out of the binary system. (Kondo, McCluskey, & Stencel 1979; Kondo, McCluskey, & Harvel 1981).

If the period is greater than some dozen days, the outflowing gas may have a chance to form an irregular ring-like structure, although patterns of gas streams similar to that seen in U Cephei can also be taking place —at least to some extent. When an amorphous ring is formed, the inner part of the ring can transfer its angular momentum to the outer part and be accreted to the companion star, with the outer part flowing out of the binary system.

4. SELECTED RESULTS FROM ULTRAVIOLET OBSERVATIONS

Ultraviolet observations provide one of the most effective means of studying mass flow phenomena in interacting binary stars. This is in part because a number of resonance lines of abundant elements are observable in the ultraviolet, e.g., Mg II at 2795 and 2802 A, Fe II at 2599 A, Si IV at 1393 and 1402 A, C IV at 1548 and 1550 A, and N V at 1238 and 1242 A. The Mg II and Fe II lines are excellent diagnostics of the gas streams, whose typical temperatures and densities favor those resonance lines, whereas the Si IV, C IV, and N V enable tracing of hot regions.

Also, light variations due to variable hot plasmas are manifested more prominently in ultraviolet than in visible light. This, by no means implies that observations in other spectral regions are not of importance. On the contrary, correlating observations from all available sources is crucial to the understanding of complex mass flows in binaries.

The 2.5-day binary U Cephei is an interesting binary. It is 'normally' considered an Algol type binary, which consists of a mass-losing late-type object and a smaller but more massive early type star that is well within its critical Roche surface. During an active mass flow episode, the binary system is engulfed in variable hot plasmas in a manner similar to β Lyrae and R Arae.

During the 'normal' phase, part of the gas stream from the G-giant strikes its B-type companion, creating a hot region on or near its surface, which covers at least part of the way around this star's equator. The rest of the gas stream plus material spraying off the impact region of the B star circulates around this star and escapes from the system. A small amount of this latter material may strike the cool companion or even interact with the gas stream after completing the circuit of the hot star. A similar gas streaming and a hot region is observed in the 3.06 day binary TX UMa (McCluskey, McCluskey, & Kondo 1988).

The first anomalous behavior of U Cephei in the ultraviolet was detected with the Astronomical Netherlands Satellite with its multi-band photometers in 1974. During the active episode in 1974–75 (Kondo, McCluskey, & Wu 1978) its ultraviolet light curves showed a secondary minimum light near phase 0.6 that becomes deeper at shorter wavelengths. Since the orbit of U Cephei is circular, a true secondary eclipse normally occurs at phase 0.5 in visible light and is shallower at shorter wavelengths as it involves an eclipse of the cooler star. Clearly, the ultraviolet light curves observed in 1974 were caused by variations in the hot plasma surrounding the system. A similar hyperactive gas flow in U Cephei was observed in ultraviolet and visible light in 1986 (McCluskey, Kondo, & Olson 1988).

The secondary minimum light was also seen to deepen in the ultraviolet light curves of the 12.9-day period binary β Lyrae (Kondo, McCluskey, & Houck 1972; Kondo et al. 1994) and in the 4.4-day binary R Arae (Kondo, McCluskey, & Parsons 1985). It is noted that Sahade (1952) was the first to point out the peculiar nature of R Arae, suggesting that it was probably similar to β Lyrae. Together with HD 207739, R Arae is in the evolutionary phase immediately preceding or following the short-lived supercritical mass flow phase (Kondo et al. 1985). U Cephei also appears to be periodically in the supercritical mass flow phase. β Lyrae may also be in the supercritical phase of mass flow but this enigmatic system resists all attempts at achieving a consistent picture of the physical processes involved.

This paper was intended as a review of the work I have personally been involved in. The papers referenced reflect this. I wish to acknowledge that a number of astronomers, whose names are not specifically mentioned here, have contributed to the advances in this field. In particular, I would like to thank my long-time colleague George E. McCluskey for helpful discussions and comments.

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