Binary evolution with relativistic jets

Ulrich Kolb\textsuperscript{a} *

\textsuperscript{a}Astronomy Group, University of Leicester, Leicester LE1 7RH, U.K.

Abstract
Relativistic jets can extract mass–energy from a black hole. In semi–detached black hole binaries the jet ejection process constitutes a ‘consequential angular momentum loss’ (CAML) process. The effect of this jet–induced CAML is to lower the transfer rate below the value set by systemic driving and to stabilize otherwise unstable systems. Implications of jet–induced CAML for GRO J1655–40 are discussed.

1. Introduction

Soft X–ray transient outbursts are widely believed to represent the bright states of an accretion disc limit–cycle, caused by the presence of partially ionised hydrogen in the disc. For this instability to operate the mass supply rate into the disc must be less than a critical value $\dot{M}_{\text{cr}}$ which would keep the disc just hot enough for hydrogen being always fully ionised. The dominant role of disc irradiation in systems with a neutron star or black hole primary makes $\dot{M}_{\text{cr}}$ much smaller than in systems with a white dwarf accretor (van Paradijs 1996, King et al. 1996).

The black hole X–ray transient source GRO J1655–40 represents a challenge for this picture as the donor’s observed location in the HR diagram — in the middle of the Hertzsprung gap (Orosz & Bailyn 1997, van der Hooft et al. 1998) — implies a transfer rate $\approx 5 \times 10^{-7} M_\odot \text{yr}^{-1}$, which is about a factor of 10 larger than $\dot{M}_{\text{cr}}$ (Kolb et al. 1997, Kolb 1998). To resolve this discrepancy it has been suggested that the donor is either in a short–lived phase where the expansion through the Hertzsprung gap slows (Kolb et al. 1997), or still on the main sequence, which could be widened by convective overshooting in the star (Regős et al. 1998).

Here we investigate a third possibility, stimulated by the observation that GRO J1655–40 is a relativistic jet source which may harbour a black hole close to maximum spin (Zhang et al. 1997, Cui et al. 1998). We show that the continuous ejection of a highly relativistic jet, powered by the black hole rotational energy, decreases the evolutionary mean mass transfer rate.

2. Mass transfer stability

The mass transfer rate in a semi–detached binary with accretor mass $M_1$ and donor mass $M_2$ is determined by the difference between the donor’s stellar radius $R$ and its Roche lobe radius $R_L$. Stationary mass transfer implies that star and lobe move in step, hence $\dot{R}/R = \dot{R}_L/R_L$. The radius change can be written as

$$\frac{\dot{R}}{R} = \frac{\dot{M}_2}{M_2} + K$$

*also Max–Planck–Institut für Astrophysik, 85740 Garching, Germany
Both the stellar (local) mass–radius index \( \zeta \) and the logarithmic radius change \( K \) in the absence of mass transfer (e.g. nuclear expansion) are determined by the donor’s structure alone. In principle they are known from stellar structure calculations. Typically \( \zeta \) varies from \(-1/3\) to 1. The Roche lobe radius changes as

\[
\frac{\dot{R}_{\text{L}}}{R_{\text{L}}} = \zeta_L \frac{\dot{M}_2}{M_2} + 2 \frac{\dot{J}_{\text{sys}}}{J},
\]

(2)

where \( \zeta_L \) is the Roche–lobe index and \( J \) the orbital angular momentum. The systemic term \( \dot{J}_{\text{sys}} \) refers to angular momentum losses with no (or negligible) mass loss from either component, e.g. gravitational wave emission. The Roche–lobe index can be obtained from the time derivative of \( J = M_1 M_2 (G a / M)^{1/2} \) (\( a \) is the orbital separation), by noting that \( R_{\text{L}} = f_2 a \), with a mass ratio–dependent geometry factor \( f_2 \). In the case of conservative mass transfer (\( J \) and total binary mass \( M \) constant) \( \zeta_L = \zeta_{L,0} = 2 M_2 / M_1 - 5/3 \) if \( M_2 \lesssim M_1 \).

Equating (1) and (2) and solving for \( \dot{M}_2 \) gives the familiar expression

\[
\frac{\dot{M}_2}{M_2} = \frac{2 \dot{J}_{\text{sys}} / J - K}{\zeta - \zeta_L}
\]

(3)

for the stationary mass transfer rate, consisting of the systemic driving (numerator) and the stability term (denominator). A simple stability analysis (e.g. King & Kolb 1995) gives \( \zeta - \zeta_L > 0 \) as a necessary condition for stable mass transfer. In most cases \( \zeta_L \) increases with mass ratio \( q = M_2 / M_1 \), hence the stability limit places an upper limit on \( q \). The transfer rate in unstable systems would grow on a timescale \( \simeq (H / R) / |\zeta - \zeta_L| \) times the mass transfer timescale (\( H \) is the photospheric pressure scale height; typically \( H / R \simeq 10^{-4} - 10^{-2} \)) to very high values. The unstable phase is usually too short to be observable. Depending on the system parameters the binary would either merge, or reappear in a stable semi–detached configuration once the mass ratio is sufficiently reduced.

3. The effect of highly relativistic jets

If the primary black hole is continuously ejecting a highly relativistic jet powered by the hole’s rotational energy, then the energy loss rate in the jet implies a corresponding loss rate \( \Gamma \dot{M}_\text{ej} \) of gravitating mass from the black hole. The quantity \( \Gamma \) specifies the jet energy loss in units of the rest mass \( \dot{M}_\text{ej} \) carried in the jet, i.e. can be significantly larger than the Lorentz factor seen in the bulk motion of the jet. As the jet ejection is a consequence of mass accretion, the rest–mass ejected in the jet must be roughly equal to the rest–mass transferred from the donor. In addition the jets will presumably carry off the specific orbital angular momentum \( j_1 = M_2 J / M_1 M \) of the black hole from the binary orbit. The jet ejection process therefore constitutes a ‘consequential angular momentum loss’ or CAML process (see e.g. King & Kolb 1995), with \( \dot{M}_1 = \Gamma M_2 - \dot{M}_2 = (\Gamma - 1) \dot{M}_2 \) and \( \dot{J}_\text{jet} = (M_2 / M_1) (J / M) \Gamma \dot{M}_2 \).

The Roche–lobe index for this jet–induced CAML is

\[
\zeta_L(\Gamma) \simeq \zeta_{L,0} - \frac{4 M_2}{3 M} \Gamma
\]

(4)

assuming \( M_2 \lesssim M_1 \). If \( q = M_2 / M_1 \) is large the expression becomes slightly more complicated as \( \frac{\partial \ln f_2}{\partial \ln q} \approx -1/3(1 + q) \) is no longer a good approximation. Further details are given in King & Kolb 1998.

Thus in the presence of jets with large \( \Gamma \) the stability denominator in (3) becomes large. This has two consequences: (a) The mass transfer rate is reduced compared to the case with conservative mass transfer. (b) Mass transfer is stable even if the mass ratio is large. Physically, the jet ejection is equivalent to a massive stellar wind from the primary which widens the orbit.
Fig. 1. Stability term (left) and mass transfer rate reduction factor (right) as a function of mass ratio $q = M_2/M_1$ for jets with different specific energy $\Gamma$.

Figure 1 shows the quantitative effect of (a) and (b). In the left panel we plot the stability term $\zeta - \zeta_L(\Gamma)$, in the right panel the factor $(\zeta - \zeta_L(\Gamma))/(\zeta - \zeta_{L0})$ by which the mass transfer rate is reduced, as a function of mass ratio, for various values of $\Gamma$. For the example shown we chose $\zeta = 0$ and used the full expression for $\zeta_L(\Gamma)$. The reduction of $(-\dot{M}_2)$ is largest close to where conservative mass transfer would be unstable.

4. Discussion

Jet–induced CAML operates if the jets are powered by the black hole’s rotational energy. The effects on the binary evolution are significant only for very energetic jets, but do not depend on the detailed mechanism of jet formation and propagation.

The duration $\Delta t$ of the phase with jet–reduced mass transfer rate turns out to be largely independent of the jet energy $\Gamma$: The extractable gravitating mass $\Delta M = g(\epsilon)M_1$ from a Kerr black hole with gravitating mass $M_1$ depends on the efficiency $\epsilon$ of the extraction process. In the case of maximal efficiency the mass can reach the irreducible value $M_1/\sqrt{2}$, i.e. $g(1) = 0.29$. For astrophysically realistic processes (e.g. Blandford & Znajek 1977) $\epsilon \lesssim 0.5$, in which case $g(\epsilon) \lesssim 0.1$ (King & Kolb 1998). Such a limit on $\Delta M_1$ implies a corresponding limit $\Delta M_{tr} = \Delta M_1/\Gamma$ for the transferred rest–mass during the jet phase. Hence the duration of the jet phase, $\Delta t \simeq \Delta M_{tr}/(-\dot{M}_2)$, is essentially independent of $\Gamma$, because the mass transfer rate also varies as $1/\Gamma$, see (3) and (4) for large $\Gamma$. We find typically $\Delta t \simeq 0.1 t_{ev}$, where $t_{ev}$ is the timescale associated with the systemic driving of mass transfer.

Jet–induced CAML would be most pronounced in black hole systems with massive donor stars. The nuclear expansion of these is rapid ($K$ in (3) large). Without jet action such systems might simply be unobservable, for a number of reasons:

1) The transfer phase is short–lived.
2) The transfer rate is super–Eddington. For an $8M_\odot$ black hole this is expected if the donor is a main–sequence star with mass $\gtrsim 6M_\odot$ (case A mass transfer), or if the donor had a mass $\gtrsim 3M_\odot$ at the end of core hydrogen burning and is now expanding to the giant branch (case B mass transfer). Mass lost from the binary might shroud the system and degrade the X–rays usually expected from such binaries.
3) The transfer rate is highly super-Eddington. Presumably a common envelope forms and the binary merges.

Jet–induced CAML could operate in GRO J1655–40 and reduce the transfer rate sufficiently to allow disc instabilities to occur. The jet would have to be very energetic (Γ ≃ 50) to decrease (−̇M₂) by more than the necessary factor of 10 for the claimed mass ratio ≃ 0.3 (Orosz & Bailyn 1997). GRS 1915+105 represents another prime candidate. There are indications that the companion star is massive (Mirabel et al. 1997), the jets are very energetic (Mirabel et al. 1998), and the black hole might be close to maximum spin (Zhang et al. 1997). It is not clear, however, if the system is semi–detached. SS433 could be affected by jet–induced CAML as well. The nature of the compact star is still unclear (e.g. Zwitter & Calvani 1989; D’Odorico et al. 1991), but a black hole cannot be ruled out. The claimed mass ratio is of order 3 or larger, so that the donor is a massive star if the accretor is indeed a black hole. Again, the donor might not fill its Roche lobe (Brinkmann et al. 1989), and the jets seem to be less energetic than in the superluminal sources.

Systems that are unstable against conservative mass transfer but stabilized by jet–induced CAML will still encounter the instability at the end of the jet phase. The mass loss rate from the hole is much larger than the mass loss rate from the donor, so that the mass ratio M₂/M₁ increases during the jet phase.

A further consequence of jet–induced CAML is that a large amount of energy is deposited into the interstellar medium. This can be as much as 10^{54} ergs if 10% of the gravitating mass of a 10M⊙ Kerr black hole has been extracted at the end of the jet phase. GRO J1655–40 would deposit this energy over a time of ≃ 10^6 yr. Zhang et al. 1997 find that the black hole spin in a number of black hole X–ray binaries is consistent with zero. It would be interesting to search for signs of past large energy deposition in the surroundings of these systems, as they might have been spun down by jets. The fact that so far no such effects are observed seems to indicate that the jet phase terminates much earlier, i.e. the black hole spin probably does not change significantly during the jet phase.

Acknowledgements I thank Andrew King for discussions and for a careful reading of the manuscript.

References

Blandford R.D., Znajek R.L. 1977, MNRAS, 179, 433
Brinkmann W., Kawai N., Matsunaka M. 1989, A&A, 218, L13
Cui W., Zhang S.N., Chen W. 1998, ApJ, 492, L53
D’Odorico S., Oosterloo T., Zwitter T., Calvani M. 1991, Nature, 352, 329
King A.R., Kolb U. 1998, MNRAS, submitted
King A.R., Kolb U. 1995, ApJ, 439, 330
King A.R., Kolb U., Burderi L. 1996, ApJ, 464, L127
Kolb U. 1998, MNRAS, 297, 419
Kolb U., King A.R., Frank J., Rüter H. 1997, ApJ, 485, L33
Mirabel, I.F., Bandyopadhyay, R., Charles, P.A., Shahbaz, T., Rodriguez, L.F. 1997, ApJ, 477, L45
Mirabel I.F., Dhawan, V., Chaty S., Rodriguez L. F., Marti J., Robinson C. R., Swank J., Geballe T. 1998, A&A, 330, L9
Orosz J.A., Bailyn C.D. 1997, ApJ, 477, 876
Regös E., Tout C.A., Wickramasinghe D. 1998, ApJ, in press
Rüter H. 1996, in Evolutionary Processes in Binary Stars, ed. R.A.M.J. Wijers, M.B. Davies, C.A. Tout, NATO ASI, Series C, Vol. 477, (Dordrecht: Kluwer), p. 223
Van der Hooft F., Heemskerk M., Alberts F., van Paradijs J. 1998, A&A, 329, 538
Van Paradijs J. 1996, ApJ, 464, L139
Zhang S.N., Cui W., Chen W. 1997, ApJ, 482, L155
Zwitter T., Calvani M. 1989, MNRAS, 236,581