Is irradiation important for the secular evolution of low-mass X-ray binaries?

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Abstract

It is argued that irradiation in low-mass X-ray binaries (LMXBs) caused by accretion-generated X-rays can not only change the optical appearance of LMXBs but also their outburst properties and possibly also their long-term evolution. Irradiation during an outburst of the outer parts of the accretion disc in a transient LMXB leads to drastic changes in the outburst properties. As far as the secular evolution of such systems is concerned, these changes can result in enhanced loss of mass and angular momentum from the system and, most important, in neutron star LMXBs in a much less efficient use of the transferred matter to spin up the neutron star to a ms-pulsar. Irradiation of the donor star can destabilize mass transfer and lead to irradiation-driven mass transfer cycles, i.e. to a secular evolution which differs drastically from an evolution in which irradiation is ignored. It is argued that irradiation-driven mass transfer cycles cannot occur in systems which are transient because of disc instabilities, i.e. in particular in long-period LMXBs with a giant donor. It is furthermore shown that for irradiating either the disc or the donor star, direct irradiation alone is insufficient. Rather, indirect irradiation via scattered accretion luminosity must play an important role in transient LMXBs and is, in fact, necessary to destabilize mass transfer in short-period systems by irradiating the donor star. Whether and to what extent irradiation in LMXBs does change their secular evolution depends on a number of unsolved problems which are briefly discussed at the end of this article.

Key words:
Accretion, accretion discs, Binaries: close, X-ray binaries,
Late stages of stellar evolution: neutron stars, pulsars
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1. Introduction

Accretion onto either the neutron star (NS)or the black hole (BH) component of a low-mass X-ray binary (LMXB) liberates copious amounts of energy, mainly as X-rays which, in turn, can irradiate either the accretion disc or the donor star of the binary system. Only gradually was it realized that irradiation in a LMXB is not just a side effect which changes its appearance but, more important, that it also changes the conditions for the occurrence of outbursts in X-ray transients (van Paradijs, 1994) and their characteristics (King & Ritter, 1998), and possibly the long-term evolution of these objects as well (Podsiadlowski, 1991). Given ample evidence that irradiation does influence LMXBs in different ways the question arises to what extent it is of importance for their long-term evolution.

The consequences would be drastic indeed if the situation modelled by Podsiadlowski (1991), namely spherically symmetric irradiation of the donor star, would really apply. However, as has been argued at length by Ritter, Zhang & Kolb (2000) (hereafter RZK), this is probably not the case. Rather the synchronously rotating donor star intercepts accretion luminosity essentially only on the hemisphere facing the source while the remaining parts are in the shadow and undisturbed. Whereas irradiation is of little consequence for "hot" stars (with an effective temperature $T_{\rm eff} \gtrsim 6500$ K) having a radiative envelope, this is not the case for "cool" stars ($T_{\rm eff} \lesssim 6500$K) with a convective envelope. As has been shown by RZK the consequences of one-sided irradiation of a cool star are rather subtle and much less drastic than what Podsiadlowski (1991) found for the case of spherically symmetric irradiation. In addition, it was found that for binary parameters which are typical for at least a significant fraction of the observed LMXB ensemble irradiation of the donor star by accretion luminosity could possibly force mass transfer to undergo what we will refer to as irradiation-driven mass transfer cycles. In this case, phases of high mass transfer, driven by the thermal expansion of the convective envelope of the irradiated donor, alternate with phases with low or no mass transfer during which the donor readjusts towards thermal equilibrium of the unirradiated star. Details about irradiation-driven mass transfer cycles may be found in RZK, Büning & Ritter (2004), and references therein.

As we have seen there are basically two ways in which accretion-generated irradiation can interfere with the evolution of a LMXB: One way is by irradiation of the accretion disk which, in turn, changes the conditions for the occurrence of disc instabilities and the outburst properties in transient systems (for a review see e.g. Lasota (2001)). Although disc instabilities occur on timescales much shorter than the evolutionary timescale of a LMXB, they can nevertheless change the outcome of binary evolution, as we shall see. The other way in which irradiation can affect binary evolution is by forcing it to undergo irradiation-driven mass transfer cycles.

In the following I shall examine in more detail the conditions for the occurrence of these two processes and their consequences for the long-term evolution of LMXBs.

2. Sources and receptors of radiation in a LMXB

Before going to examine the processes mentioned above it is perhaps useful to have a look at the possible sources and receptors of radiation in a LMXB and the conditions that have to be fulfilled in order for irradiation to play a role at all.

The possible sources and receptors of radiation can be conveniently subdivided into: (1) the compact star, (2) the inner parts of the accretion disc and the accretion disc corona, (3) the outer parts of the disc, and finally (4) the donor star. (The "inner parts of the disc" include a possible boundary layer and those parts of the disc where most of the binding energy is liberated.) Of course, not all combinations of source $(i),\ i = 1, \ldots, 4$ irradiating receptor $(j),\ j = 1, \ldots, 4$ are possible or of relevance. In order to be of importance the radiation produced by the source has to meet two conditions: first it has to be hard (penetrating) enough to reach the receptor and penetrate below its photosphere, and second its flux density at the receptor should be at least comparable to if not exceeding the receptor's intrinsic flux. Excluding self-irradiation this leaves us essentially with the following combinations: Irradiation of the inner and outer disc as well as the donor star by the compact star (here the neutron star), and irradiation of the outer disc and the donor star by the inner disc and corona (which is of relevance if the compact object is a black hole).

3. Effects of irradiation

3.1. *Effects on the disc*

The main effects of irradiating the accretion disc which are of relevance here can be summarized as follows (for details see e.g. van Paradijs (1994), King & Ritter (1998), Lasota (2001), Ritter & King (2001)):

– Whereas viscous heating keeps the effective temperature $T_{\rm eff}$ of the disc above the hydrogen ionization temperature $T_{\rm H} \approx 6500$ K inside a radius

$$R_{\rm h,visc} \approx 0.66\ {\rm R}_\odot\ {m_{\rm c}}^{1/3} \dot{M}_{\rm tr,-8}^{1/3}\,, \qquad (1)$$

where $m_{\rm c}$ is the mass of the compact star in ${\rm M}_\odot$ and $\dot{M}_{\rm tr,-8}$ the mass transfer rate in units of $10^{-8}{\rm M}_\odot/{\rm yr}$, irradiation, following King & Ritter (1998), keeps $T_{\rm eff}$ in the disc of a neutron star LMXB above $T_{\rm H}$ inside a radius

$$R_{\rm h,irr} \approx 7.1\ {\rm R}_\odot\ \dot{M}_{\rm tr,-8}^{1/2}\,. \qquad (2)$$

As a consequence of this, for a binary of given orbital period $P_{\rm orb}$, stationary accretion is possible for lower mass transfer rates than without irradiation, or for longer $P_{\rm orb}$ for a given $\dot{M}_{\rm tr}$.

For a black hole LMXB, again using parameters of King & Ritter (1998), one obtains

$$R_{\rm h,irr} \approx 2.7\ {\rm R}_\odot\ \dot{M}_{\rm tr,-8}^{1/2}\,. \qquad (3)$$

– In cases where disc accretion is non-stationary, e.g. if the donor is a giant and $P_{\rm orb}$ long, in an outburst irradiation delays the return to quiescence. As a consequence, the disc is emptied to a much larger degree and this, in turn, results in a much longer quiescence (mass accumulation phase) beteween outbursts.
– Furthermore, in long-period systems a much larger part of the disc, i.e. much more mass is actively involved in an outburst. This results in much higher mass flow rates $\dot{M}_{\rm d}$ through the disc, rates which can be much larger than the Eddington accretion rate $\dot{M}_{\rm Edd}$ of the compact star. And this, in turn, leads to significant loss of mass and angular momentum from the binary system.

3.2. *Effects on the donor star*

The most important effects resulting from irradiating the donor star can be summarized as follows (for details see e.g. Podsiadlowski (1991), RZK and Büning & Ritter (2004)):
– For "hot" stars ($T_{\rm eff} \gtrsim 6500\,{\rm K}$, radiative envelope) irradiation is of little consequence.
– For cool stars with a convective envelope ($T_{\rm eff} \lesssim$ 6500 K) irradiation, by lowering the superadiabatic temperature gradient in the subphotospheric layers, hinders the star's energy loss from the interior through the irradiated parts of its surface. As a result, the flux $F_{\rm int}$ which such a star can lose from its interior is the lower the higher the irradiating flux $F_{\rm irr}$ [1] . As an example, the relation $F_{\rm int}(F_{\rm irr})$ as derived from numerical calculations (Hameury & Ritter, 1997) is shown in Fig. 1 for a number of cool low-mass stars.
– Upon onset of irradiation, an initially undisturbed cool star will expand on the timescale $\tau \approx \tau_{\rm ce}/s_{\rm eff}$, where $\tau_{\rm ce}$ is the thermal timescale of the convective envelope, and $s_{\rm eff}$ the effective fraction of the stellar surface through which energy loss from its interior is blocked. An example of a numerical calculation of the thermal relaxation process of a low-mass ($0.4{\rm M}_\odot$) star is shown in Fig. 2. In a semi-detached binary this expansion drives additional mass transfer and thus leads to increased accretion luminosity and hence irradiating flux.
– Because the thermal relaxation process, i.e. the radius increase, saturates with time (see top panel in Fig. 2) and in amplitude (meaning that no more than the total intinsic flux can be blocked), in a semi-detached binary this leads to the possibility of irradiation-driven mass transfer cycles mentioned earlier. Whether such mass transfer cycles do appear depends on whether mass transfer is thermally stable. A detailed discussion of this problem is beyond the scope of this paper. For this the reader is referred to King et al. (1996), King et al. (1997), RZK, and Büning & Ritter (2004). If mass transfer is unstable and cycles do occur, then phases of high mass transfer alternate with phases of low or no mass transfer during which the donor readjusts towards thermal equilibrium of the unirradiated star.
– For a partially irradiated cool star the relative radius increase saturates at a value

$$\Delta R/R \approx (1 - s_{\rm eff})^{-\rho} - 1\,, \tag{4}$$

where $\rho \approx 0.1$ for low-mass main sequence stars, and $\rho \approx 0.5$ for giants. Thus, for any value of $s_{\rm eff}$ which is not very close to unity the relative radius increase is much smaller than what Podsiadlowski (1991) had found for saturated, spherically symmetric irradiation, whereby the stellar envelope becomes radiative.
– Upon sustained or slowly varying irradiation an isolated irradiated star attains a new thermal equilibrium radius

$$R_{\rm e}(s_{\rm eff}) \approx R_{\rm e}(0)\;(1 - s_{\rm eff})^{-\rho}. \tag{5}$$

In a mass transferring binary the irradiated donor cannot attain thermal equilibrium. Nevertheless, for a given mass and mass loss rate the irradiated star is systematically oversized compared to the case where irradiation is ignored.

4. Consequences for the secular evolution of neutron star LMXBs

4.1. *Consequences from disc irradiation*

Depending on whether the disc radius $R_{\rm d} \lessgtr R_{\rm h}(\dot{M}_{\rm tr})$ disc accretion is stable (<) or unstable (>). Since $R_{\rm h,irr} > R_{\rm h,visc}$ for all values of $\dot{M}_{\rm tr}$ of interest (cf. Eqs. (1) and (2)), disc irradiation widens the parameter space for systems with stable disc accretion. Using standard parameters for describing an irradiated disc (King & Ritter, 1998) and assuming $R_{\rm d}$ to be 80% of the Roche radius of

[1] To be precise: $F_{\rm irr}$ hereafter denotes the perpendicular component of that fraction of the external irradiating flux which is absorbed below the photosphere.

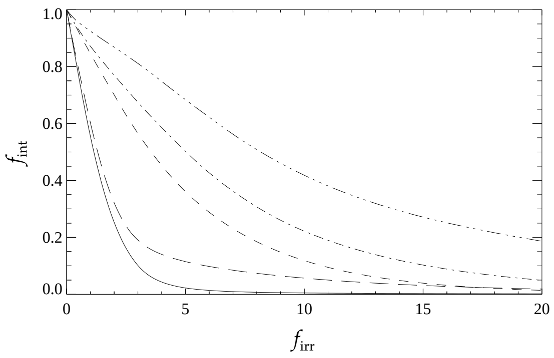

Fig. 1. $f_{\rm int} = F_{\rm int}/F_0$ (F_0 being the intrinsic flux of the unirradiated star) as a function of $f_{\rm irr} = F_{\rm irr}/F_0$ for five different stellar models characterized by their evolutionary state and the following combination of mass and central hydrogen abundance $(M, X_{\rm c})$: full line: ZAMS, (0.3, 0.71); long–dashed line: ZAMS, (0.5, 0.71); short-dashed line: ZAMS, (0.8, 0.71); dash-dotted line : near the TAMS, (0.45, 0.05), and dot-dash-dotted line: giant with a radius of $R = 25.8 {\rm R}_\odot$, (0.8, 0.0). From Büning & Ritter (2004).

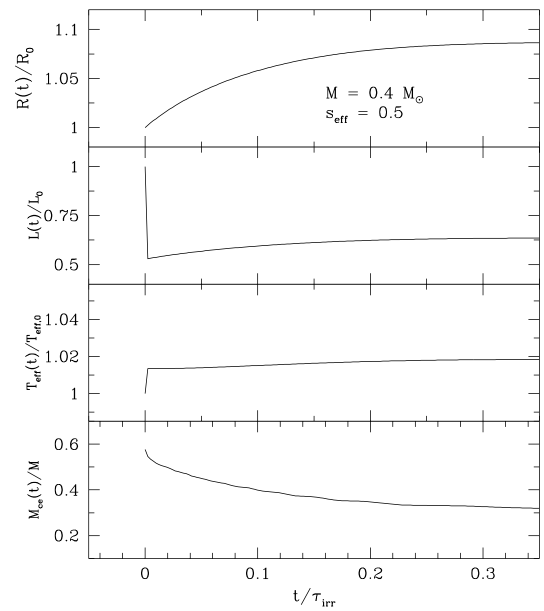

Fig. 2. Thermal relaxation of a $0.4 {\rm M}_\odot$ main sequence star after blocking the energy loss over a fraction $s_{\rm eff} = 0.5$ of its surface at time $t = 0$. Top frame: radius R, second frame: luminosity L, third frame: effective temperature $T_{\rm eff}$ of the unirradiated part, and bottom frame: the relative mass $M_{\rm ce}/M$ of the convective envelope as a function of time. Time is measured in units of the timescale on which the radius grows at $t = 0$. R_0, L_0, and $T_{\rm eff,0}$ are respectively the values of R, L and $T_{\rm eff}$ immediately before the onset of the blocking of energy outflow (from RZK).

the compact component, the critical orbital period, $P_{\rm crit}$, for which $R_{\rm d} = R_{\rm h,irr}$, is

$$P_{\rm crit} \approx 9.8 \text{ d } m_{\rm c}{}^{-0.675} m_{\rm d}{}^{0.175} \dot{M}_{\rm tr,-8}^{3/4}\,, \qquad (6)$$

where $m_{\rm d}$ is the mass of the donor in ${\rm M}_\odot$. Accordingly, most of the short-period neutron star LMXBs ($P_{\rm orb} \lesssim 2$ d) should have stationary discs. And for such systems it appears, at least at first glance, that irradiation is of little consequence for their long-term evolution. However, as we shall see below, it is exactly these systems for which irradiation-driven mass transfer cycles are most likely to occur, and with them the consequential changes of their long-term evolution.

If, on the other hand, $P_{\rm orb} > P_{\rm crit}$ disc accretion is unstable and such systems are X-ray transients. As we have already noted above, because $R_{\rm h,irr}$ is significantly bigger than $R_{\rm h,visc}$ (cf. Eqs. (1) and (2)), a much larger part of the disc is involved in an outburst than would be the case without irradiation. Therefore, much more mass is actively involved in an outburst. Because of irradiation, it also takes longer for the disc to return to quiescence. This happens only after the disc is almost totally emptied. For a given mass transfer rate this means that the quiescene, i.e. the mass accumulation time between two consecutive outbursts, is correspondingly longer. In addition, the mass flow rate through the disc during an outburst is the larger the longer the orbital period. In fact, for transient systems the mass flow rates are typically much above the Eddington rate of a neutron star (see e.g. Ritter & King (2001)). In this context it is important to note that in long-period systems, i.e. with $P_{\rm orb} \gtrsim 20$ d, undergoing nuclear timescale-driven mass transfer from a giant, even the time-avaraged mass transfer rate which is roughly $\propto P_{\rm orb}$ exceeds the Eddington accretion rate of a neutron star (e.g. Ritter (1999)). This, in turn, has two consequences for the evolution of a LMXB: First, super-Eddington mass flow rates lead to substantial loss of mass and angular momentum from the binary system and thus to an evolution which differs from that of an LMXB where irradiation has been ignored. Second, super-Eddington mass flow rates also mean that only a (small) fraction of the transferred matter can be accreted by the neutron star. And that fraction is the smaller the longer $P_{\rm orb}$. In this way irradiation of the disc hinders or, in long-period systems ($P_{\rm orb} \gtrsim$ few 10^2 d), may even prevent the spin-up of the neutron star and thus the formation of millisecond pulsars (Ritter & King, 2001).

To make matters worse, at least as far as the formation of millisecond pulsars is concerned, during the long-lasting quiescence the neutron star could be significantly spun down by becoming a propeller (see below Sect. 7.3).

4.2. *Consequences from irradiating the donor star*

As has already been detailed in Sect. 3.2 irradiating a low-mass donor star in a LMXB can destabilize mass transfer and give rise to irradiation-driven mass transfer cycles. If mass transfer is thermally stable and no mass transfer cycles do occur, irradiation is of little consequence for the long-term evolution of the binary system. If, however, mass transfer is thermally unstable, the evolution of a LMXB, undergoing mass transfer cycles, is totally different from that without irradiation. Mass transfer is spasmodic with phases of high mass transfer driven by the thermal expansion of the convective envelope of the irradiated donor alternating with phases with low or no mass transfer during which the donor readjusts towards thermal equilibrium of the unirradiated star. Because the thermal timescale of the convective envelope can be rather short, the mass transfer rate during a high state can exceed the Eddington accretion rate of a neutron star by a large factor. And this results in the same effects as have already been discussed in Sect. 3.1, namely in considerable loss of mass and angular momentum from the system and low accretion efficiency of the neutron star. This, in turn, hinders the spin-up of the neutron star and thus possibly the formation of a ms-pulsar. In the low state the binary is more or less detached and the mass transfer rate is either very low or virtually zero. Thereby the duration of the low state is proportional to the timescale on which mass transfer is driven and, therefore, can be very long. And, of course, during the long phases with little or no mass transfer the previously spun-up neutron star can be spun down again by the action of the propeller mechanism (see below Sect. 7.3).

An example (from Büning & Ritter (2004)) for how different the evolution of a neutron star LMXB can be, depending on whether irradiation is taken into account or not, is shown in Fig. 3. The parameters and assumptions used for these calculations were as follows: for the neutron star: initial mass $M_{\rm NS} = 1.4{\rm M}_\odot$, radius $R_{\rm NS} = 10^6$cm; for the donor star at the onset of mass transfer $M_{\rm d} = 3{\rm M}_\odot$ and central hydrogen content $X_{\rm c} = 0.36$; angular mo-

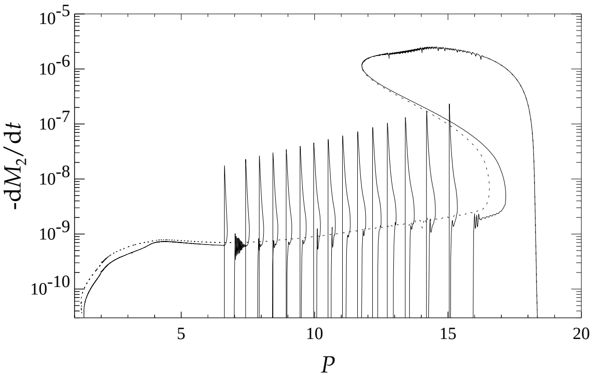

Fig. 3. Mass transfer rate (in $\mathrm{M}_\odot$/yr) as a function of the orbital period (in d) of a model LMXB with (full line) and without (dotted line) taking irradiation into account. For details see text. From Büning & Ritter (2004).

mentum loss by gravitational radiation and magnetic braking according to Verbunt & Zwaan (1981) with $f_{\rm VZ} = 1$; conservative mass transfer as long as $\dot M_{\rm tr} < \dot M_{\rm Edd} = 2\ 10^{-8}{\rm M}_\odot/{\rm yr}$, and loss of mass and angular momentum in the Jeans mode with $\dot M_{\rm loss} = \dot M_{\rm tr} - \dot M_{\rm Edd}$ if $\dot M_{\rm tr} > \dot M_{\rm Edd}$; irradiation of the donor by a point source at the location of the neutron star with a flux equal to 10% of the perpendicular component of the isotropic flux resulting from the accretion luminosity $L_{\rm acc} = GM_{\rm NS}\dot M_{\rm accr}/R_{\rm NS}$, and ignoring the shadow cast by the disc onto the donor. As can be seen from Fig. 3, after an initial phase of thermally unstable mass transfer, if irradiation is taken into account irradiation-driven mass transfer cycles start to appear. Thereby the mass transfer rate during the high state of a mass transfer cycle can exceed the time-averaged mass transfer rate by up to two orders of magnitude and $\dot M_{\rm Edd}$ by up to a factor of 10. This shows that it makes really a big difference for the long-term evolution of a LMXB whether or not irradiation-driven mass transfer cycles do occur.

Such differences are even more extreme if the donor star is a giant. There are two main reasons for this: First, as can be seen from Eq. (4), with $\rho \approx 0.5$ the amplitude of the irradiation effect for a given value of $s_{\rm eff}$ is much higher than for a main sequence star, where $\rho \approx 0.1$. This is a direct consequence of the core mass-luminosity relation: upon expansion of the convective envelope of a giant the nuclear energy generation is not quenched, in contrast to what happens in main sequence stars. Second, because of the much larger radius R and luminosity L of a giant compared to a typical low-mass main sequence star, the thermal timescale of

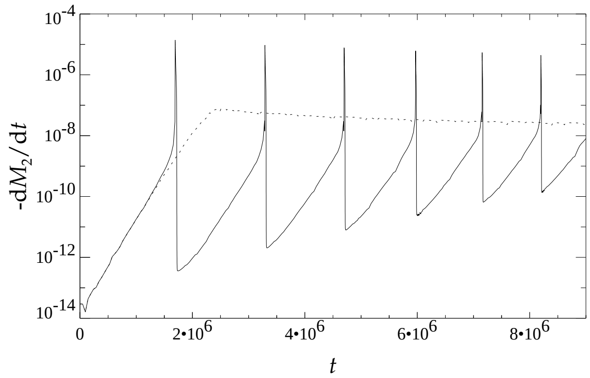

Fig. 4. Mass transfer rate (in $M_\odot$/yr) as a function of time t (in yr) of a model LMXB with a giant donor with (full line) and without (dotted line) taking irradiation into account. For details see text. From Büning & Ritter (2004).

the convective envelope $\tau_{\rm ce}$ (being proportional to the Kelvin-Helmholtz time $\tau_{\rm KH} \propto (RL)^{-1}$) is much shorter and, therefore, the irradiation-driven mass transfer rate $\dot M_{\rm tr} \propto M/\tau_{\rm ce}$ correspondingly higher.

This is illustrated by the results of a computation by Büning & Ritter (2004) shown in Fig. 4. In this case the parameters and assumptions used for the model calculation were as follows: for the neutron star: initial mass $M_{\rm NS} = 1.4 M_\odot$, radius $R_{\rm NS} = 10^6$ cm; the donor star at the onset of mass transfer is a giant with $M_{\rm d} = 0.8 M_\odot$ and a radius $R_{\rm d} = 25.8 R_\odot$; mass transfer is driven by nuclear evolution of the donor and assumed to be conservative; irradiation of the donor by a point source at the location of the neutron star with a flux equal to 10% of the perpendicular component of the isotropic flux resulting from the accretion luminosity $L_{\rm acc}$, and ignoring the shadow cast by the disc onto the donor.

In this example, if mass transfer cycles do occur, mass transfer proceeds in very short bursts during which exceedingly high mass transfer rates are reached (up to $\dot M_{\rm tr} \approx 10^{-5} M_\odot$/yr), each of which is followed by a long detached phase lasting typically $\sim 10^6$ yr.

Whether or not irradiation-driven mass transfer cycles do occur also makes a big difference when it comes to estimating the intrinsic number of LMXBs e.g. in the Galaxy. Since the high state of such a mass transfer cycle lasts much longer than the $\sim$ 40 yr since we observe LMXBs we actually see only a small fraction of those systems undergoing mass transfer cycles, namely those which are currently in a high state. And that fraction is roughly the average duty cycle $\langle d \rangle = \langle t_{\rm high}/t_{\rm cycle} \rangle$. Given that the peak mass transfer rate can exceed the time-averaged mass transfer rate by several orders of magnitude (see Figs. 3 and 4), the occurrence of irradiation-driven mass transfer cycles would also imply the existence of a large and hidden population of LMXBs being in the low state of the cycle.

5. Consequences for the secular evolution of black hole LMXBs

5.1. *Consequences from disc irradiation*

When comparing Eq. (1) with Eq. (3) we see that also in the case of a black hole LMXB $R_{\rm h,irr} > R_{\rm h,visc}$ for any value of $\dot M_{\rm tr}$ of interest and that also in this case irradiation of the disc widens the parameter space for systems with stable disc accretion. Following again King & Ritter (1998) and using standard parameters for a black hole LMXB, and assuming $R_{\rm d}$ to be 80% of the Roche radius of the compact component the critical orbital period separating transient from non-transient systems is

$$P_{\rm crit} \approx 2.3 \text{ d } m_{\rm c}{}^{-0.675} m_{\rm d}{}^{0.175} \dot M_{\rm tr}^{3/4} \, . \tag{7}$$

As in the case of neutron star LMXBs disc irradiation in black hole LMXBs is of little consequence for the long-term evolution as long as $P_{\rm orb} < P_{\rm crit}$, i.e. as long as disc accretion is thermally stable, apart from the fact that stable disc accretion is a prerequisite for the occurrence of irradiation-driven mass transfer cycles. However, as has first been pointed out by King, Kolb & Burderi (1996), practically all black hole LMXBs with a non-compact donor star must be transient. Apart from the fact that in a black hole LMXB irradiation is less efficient than in a neutron star LMXB and, therefore, $P_{\rm crit}$ is smaller, the main reason for this is that the mass of the black hole $M_{\rm BH}$ is significantly higher than the mass of a typical neutron star, i.e. $\langle M_{\rm BH} \rangle \approx 3 - 10 \, \langle M_{\rm NS} \rangle$. Therefore, the mass ratio $M_{\rm c}/M_{\rm d}$ is larger by a corresponding factor, and this, in turn, results in lower mass transfer rates because, on the one hand, mass transfer is the more stable the larger $M_{\rm c}/M_{\rm d}$, and, on the other hand, because the rate of loss of orbital angular momentum is smaller for larger $M_{\rm c}/M_{\rm d}$ (at least for the often-used prescription of "magnetic braking" by Verbunt & Zwaan (1981)).

Another consequence of having a black hole accretor rather than a neutron star is that the relevant Eddington accretion rate $\dot M_{\rm Edd} \propto M_{\rm c}$ is higher, on average by a factor $\langle M_{\rm BH}/M_{\rm NS} \rangle \approx 3 - 10$. And this means that supper-Eddington accretion is less likely to occur. This applies even more to the (hypothetical) non-transient systems. In the end this means that in black hole LMXBs the mass and consequential angular momentum losses are systematically smaller than in neutron star LMXBs. Yet because $R_{\rm h,irr} > R_{\rm visc}$ a larger part of the disc is actively involved in an outburst and thus during an outburst the mass flow rate through the disc is systematically higher than what one would have in a non-irradiated disc. As a consequence, super-Eddington rates and associated mass and consequential angular momentum loss can nevertheless result in systems where none would occur in the absence of irradiation.

5.2. *Consequences from irradiating the donor*

Because, as we have seen in the previous section, practically all black hole LMXBs are transient, irradiation of the donor star is intermittent on timescales short compared to the thermal timescale of the donor's convectiec envelope $\tau_{\rm ce}$. For reasons which we shall discuss in the next section, irradiation-driven mass transfer cycles are not expected to occur under these circumstances.

6. Disc instabilities and mass transfer cycles at the same time in the same system?

So far I have dealt with disc instabilities and irradiation-driven mass transfer cycles as separate issues. The question is now whether both could occur in the same system at the same time. And, as I shall show below, the answer is: **No**. In order to understand why this is so it is necessary to first have a closer look at the prerequisits for irradiation-driven mass transfer cycles to occur:

6.1. *Conditions for irradiation-driven mass transfer cycles*

The list given below of conditions which favour the occurrence of mass transfer cycles follows directly from the discussion of thermal stability of mass transfer as given e.g. in RZK, King et al. (1996), King et al. (1997), and Büning & Ritter (2004).

(i) *Sustained irradiation with a flux $F_{\rm irr} \approx F_{\rm int}$ over at least a thermal timescale of the convective envelope $\tau_{\rm ce}$.*

If this condition is violated, i.e. if either $F_{\rm irr}$ is small or irradiation is intermittent, i.e. if phases of irradiation with high flux but short duration $\Delta t_{\rm irr} < \tau_{\rm ce}$ alternate with phases with very little or no irradiation, blocking of intrinsic flux is inefficient . The reason for this is the run of the function $F_{\rm int}(F_{\rm irr})$, examples of which are shown in Fig. 1. Because of the non-linearity of this function, i.e. because no more than the intrinsic flux F_0 of the unirradiated star can be blocked, the maximum amount of energy blocked for a given amount of accretion luminosity is achieved by continuous irradiation with the time-averaged flux. And although the blocking of intrinsic luminosity is highest for the highest irradiating fluxes, continuous irradiation with very high fluxes $F_{\rm irr} \gg F_{\rm int}$ does not help either because for mass transfer to be unstable $-dF_{\rm int}/dF_{\rm irr}$ must not be too small. This is the case only for fluxes $F_{\rm irr}/F_0 \lesssim 1, \ldots,$ few. On the other hand, for large $F_{\rm irr}$, $dF_{\rm int}/dF_{\rm irr} \rightarrow 0$, and mass transfer is stable despite irradiation.

The extent to which intermittent irradiation can suppress the occurence of irradiation-driven mass transfer cycles has been examined by King et al. (1997) by adopting a simplified $F_{\rm int}(F_{\rm irr})$-relation and a "top hat model" for the temporal variation of the accretion rate. Not surprisingly, it is found that mass transfer is the more thermally stable the smaller the duty cycle of the intermittency of irradiation is.

(ii) *A small value of $\tau_{\rm ce}/t_{\rm dr}$*, where $t_{\rm dr}$ is the timescale on which mass transfer is driven, i.e. $t_{\rm dr} = (1/t_{\rm nuc} + 2/t_{\rm J})^{-1}$. Here $t_{\rm nuc}$ is the timescale on which the radius of the donor grows in response to nuclear evolution alone, and $t_{\rm J}$ the timescale on which orbital angular momentum (in the absence of mass transfer) is lost. For this condition to be fulfilled either $\tau_{\rm ce}$ has to be sufficiently small or $t_{\rm dr}$ not too short. The former is the case either for main sequence stars having a relatively shallow convective envelope or for giants, the latter for binary systems losing orbital angular momentum at the minimum possible rate, i.e. via gravitational radiation only.

(iii) *A small photospheric scale height H of the donor, more precisely $H/R_{\rm d} \ll 1$.*

The smaller $H/R_{\rm d}$ the larger the derivative $d\dot{M}_{\rm tr}/dR_{\rm d}$ (e.g. (Ritter, 1988)), i.e. the more violent the reaction of the system upon an irradiation-driven change of the donor's radius. Typical values are $H/R \approx 10^{-4}$ for main sequence stars and $10^{-2} \lesssim H/R \lesssim 10^{-3}$ for giants.

(iv) *A small value of* $R_{\rm c}/R_{\rm d}$.

Since for a LMXB $R_{\rm c}$ is already minimal, $R_{\rm c}/R_{\rm d}$ is necessarily small, unless the donor is a compact star, and systematically smaller for a giant donor than for a main sequence star.

(v) *A sufficiently large fraction of the stellar surface has to be exposed to a flux* $F_{\rm irr} \approx F_{\rm int}$.

If the source of irradiation is modelled as a point source and the shadow cast by the disc onto the donor star is ignored, a fraction $s_{\rm PS} = R_{\rm d}/a \approx 0.3-0.4$ of the donor's surface "sees" the source. Here a is the orbital separation of the two stars. However, the effective fraction of the surface $s_{\rm eff}$ over which $F_{\rm int}$ is blocked can be considerably smaller than $s_{\rm PS}$ because the perpendicular component of the irradiating flux (this is the quantity that is relevant here) varies considerably from the substellar point to the termiator: If $F_{\rm irr} \approx F_{\rm int}$ near the substellar point, then $F_{\rm irr}$ is small (and so is the blocking of intrinsic flux) far from it. On the other hand, if $F_{\rm irr} \approx F_{\rm int}$ far from the substellar point then closer to it $F_{\rm irr} \gg F_{\rm int}$, i.e. the blocking effect saturates, and $s_{\rm eff} \to s_{\rm PS}$. Things get even more unfavourable if the disc shadow is taken into account: The fact that few LMXBs show deep eclipses has always been interpreted as evidence for the outer parts of the disc to be flared to the extent that practically no part of the donor "sees" the disc's center. Turning the argument around this means that in a LMXB no part or at most small regions near the polar caps can be directly rradiated by a point source located at the disc's center.

6.2. *Consequences for systems with a giant donor*

As we have seen in Sect. 4.1 in systems with a giant donor fulfilling the criterion $P_{\rm orb} > P_{\rm crit}$, where $P_{\rm crit}$ is given by either Eq. (6) or Eq. (7), disc instabilities are unavoidable. Hence the irradiation resulting from accretion is intermittent on a timescale which is essentially given by the low state viscous timescale of the "active" accretion disc (Ritter & King, 2001). And that, in turn, is of the order of $\sim 10-10^3$ yr, and thus much shorter than $\tau_{\rm ce}$ of the associated giant donor. Therefore, systems with a giant donor and $P_{\rm orb} > P_{\rm crit}$ violate the first of the above criteria, and this is already enough to suppress irradiation-driven mass transfer cycles in LMXBs with $P_{\rm orb} > P_{\rm crit}$.

In this sense, the calculation shown as a full line in Fig. 4 is irrelevant. After what has been said above, systems undergoing such an evolution should not exist. And we have indirect evidence that this is indeed the case, namely the existence of ms-pulsars in binary systems with orbital periods even as long as a few 10^2 d. If such LMXBs would really evolve with irradiation-driven mass transfer cycles and behave as shown in Fig. 4 (full line), the total amount of mass the neutron star could accrete during the comparatively very short high states would be very small and the angular momentum accreted with it insufficient to spin the neutron star up to a spin period of a few milliseconds.

6.3. *Consequences for systems with a main sequence donor*

As we have seen, virtually all black hole LMXBs, even those with a main sequence donor, must be transient (c.f. Eq. (7)). Therefore, irradiation is intermittent and irradiation-driven mass transfer cycles are suppressed.

On the other hand, neutron star LMXBs with stable disc accretion are possible (c.f. Eq. (6)). In fact, irradiation, by suppressing disc instabilities, widens the parameter space for stable disc accretion, and for such systems the occurrence of irradiation-driven mass transfer cycles cannot be ruled out a priori. As we shall discuss in the next section, the main problem here is calculating $s_{\rm eff}$, i.e. $F_{\rm irr}$, in the context of a reliable model of a LMXB.

Finally, also in transient neutron star LMXBs irradiation-driven mass transfer cycles are suppressed because irradiation of the donor is intermittent.

7. Open problems

7.1. *Direct versus indirect irradiation*

One of the most serious problems, if not the most serious one, arising in the contex of our topic is how to calculate $F_{\rm irr}$ for each surface element of the object of interest, i.e. either the (outer parts of the) accretion disc or the donor star. As has e.g. been shown by Dubus, Hameury & Lasota (2001) this is already a non-trivial task in one of the simplest cases imaginable, i.e. a planar, axisymmetric concave disc being irradiated by a central point source.

The situation is considerably more complicated when considering that in going to outburst an initially cool disc is transformed into a hot disc out to some radius $R_{\rm h,irr} > R_{\rm h,visc}$ (cf. Eqs. (1) and, respectively, (2) or (3)). Whereas a central point source can keep the disc hot, i.e. at $T_{\rm eff} > T_{\rm H}$, in the region $R_{\rm h,irr} > r > R_{\rm h,visc}$, it cannot transform the same region from the cool state into the hot state because in the cool state these regions are in the (point source) shadow cast by the inner, hot parts of the disc. Since the observed long durations of the outbursts of X–ray transients are a natural outcome of assuming that in outburst the disc is in the hot state out to some radius $R_{\rm h,irr} > R_{\rm h,visc}$ (see e.g. King & Ritter (1998) and Dubus, Hameury & Lasota (2001)), we are practically forced to the conclusion that indirect irradiation, i.e. scattered light, must be involved. And, as the following estimate shows, this is not inconceivable because only a small fraction of the isotropic accretion flux $F_{\rm accr} = L_{\rm accr}/4\pi r^2$ needs to be scattered towards the disc in order to raise its temperature above $T_{\rm H}$ out to some radius $r \leqq R_{\rm h,irr}$. Since the required scattered flux is $F_{\rm irr} \approx \sigma {T_{\rm H}}^4$ we find that, assuming an X-ray albedo of ~ 0.1, $F_{\rm irr}/F_{\rm accr} \lesssim 10^{-3}(r/R_\odot)^2$ for a neutron star or a black hole LMXB. (Note that for this estimate using Eq. (2) or (3) for $R_{\rm h,irr}$ is inappropriate because these expressions have been derived by assuming direct irradiation.) Invoking indirect irradiation also requires that the irradiating source, i.e. the scattering corona, is sufficiently extended. Of course, once the disc has been brought to the hot state in which it is concave for radii $r < R_{\rm h,irr}$ (whereby it is unclear whether in this case $R_{\rm h,irr}$ is adequately approximated by respectively Eq.(2) or (3)), direct irradiation will also contribute, in addition to scattered light.

Calculating $F_{\rm irr}$ is not only a problem when dealing with irradiated discs in X-ray transients, but even more so when dealing with an irradiated donor star in the context of irradiation-driven mass transfer cycles. First, it is important to note that for bright LMXBs direct irradiation probably does not work. On the one hand, in the presence of a stationary hot accretion disc which casts a broad point source shadow onto the donor star, only relatively small areas near the poles of the donor's facing hemisphere are directly irradiated by the central source, and that at near grazing incidence. Although details have not been worked out so far, it is very probable that this is insufficient to destabilize mass transfer. On the other hand, even if one ignores the shadow cast by the disc onto the donor star mass transfer is not likely to be unstable. The reason for this has already been discussed above (point (v) in Sect. 6.1): in LMXBs with a low-mass main sequence donor [2], i.e. with $M_{\rm d} \lesssim 1\ M_\odot$, the ratio $F_{\rm irr}/F_{\rm int}$ near the substellar point is typically much larger than unity even for small values of the X-ray albedo (of order $\lesssim 0.1$). And this is also the case for most parts of the facing hemisphere except for small regions at high latitude where irradiation is nearly grazing. Therefore, as far as the stability of mass transfer is concerned, the situation is not unlike the one where the disc's shadow is taken into account: only a small fraction of the stellar surface is exposed to irradiation and at the same time sufficiently sensitive to *changes* in $F_{\rm irr}$.

Since direct irradiation is unlikely to destabilize mass transfer in a LMXB we are now going to examine whether indirect irradiation could do the job. The first thing to note in this context is that if in wide, transient LMXBs scattered X-rays are intense enough to raise the effective temperature of the outer parts of an otherwise cool disc above $T_{\rm H} \approx 6500$ K they will also be intense enough to result in ratios $F_{\rm irr}/F_{\rm int} \gtrsim 1$ on the donor star of a typical short-period, non-transient LMXB. As we had argued above (point (i) in Sect. 6.1) such values of $F_{\rm irr}/F_{\rm int}$ are optimal for inducing mass transfer cycles. The other question is whether a sufficiently large fraction of the donor's surface is exposed to scattered light. This depends entirely on the size of the scattering corona. If it is small compared to the orbital separation, the disc will nevertheless cast an extended shadow onto the donor, and irradiation, affecting too small an area, will probably not destabilize mass transfer. If, on the other hand, the irradiating source is sufficiently extended, not only will the shadowing of the disc be much less significant. In addition, regions on the donor star which are well beyond the point source terminator could be significantly affected by indirect irradiation. Clearly, calculating $F_{\rm irr}$ over the surface of the donor star under these circumstances is no simple task. And, not surprisingly, hitherto no such calculations, though urgently needed, have been carried out. For this reason

[2] as we have argued above, only for such systems irradiation-driven mass transfer cycles could possibly occur

it is currently also impossible to say whether LMXBs could undergo irradiation-driven mass transfer cycles.

7.2. *The disc instability model*

Adequate modelling of the spin-up of a neutron star to a ms-pulsar in a long-period, transient LMXB requires detailed knowledge of how (how much and for how long) mass is flowing through the accretion disc onto the neutron star during an ouburst. This necessarily involves the thermal-viscous disc instability model for discs subject to irradiation during an outburst. And, although numerical simulations of one or a few such outbursts for a few sets of parameters have been carried out (see e.g. Dubus, Hameury & Lasota (2001), and references therein), such calculations are not sufficient for the task at hand: after all we are talking here about the entire phase of mass transfer from a giant donor which can last up to $\sim 10^8$ yr (e.g. Ritter (1999)), i.e. a time during which the disc undergoes a huge number of outbursts under secularly changing conditions. No question that, at least at present, this could be dealt with by means of a sequence of detailed numerical disc instability model calculations . What is really needed is a reasonably simple yet sufficiently accurate analytical or semi-analytical model of disc instabilities which provides the entire manifold of solutions. Whereas a viable model for the outburst phase, during which the active disc (that is the part of the disc involved in an outburst) is in a quasi-stationary state, can be formulated (Ritter & King, 2001), this has so far not been possible for the quiescent phase during which the active disc is not nearly stationary. On top of that any viable model has also to take into account that all the important properties of an outburst cycle are strongly influenced by the fact that during quiescence matter in the central part of the disc evaporates into an advection-dominated accretion flow (Meyer & Meyer-Hofmeister (1994), Liu, Meyer & Meyer-Hofmeister (1997), Meyer, Liu & Meyer-Hofmeister (2000), Dubus, Hameury & Lasota (2001), and references therein). Thereby a central hole is formed, the size of which essentially determines the storage capacity of the disc and thus the duration of quiescence. Until such a model becomes available, the spin-up of a neutron star to a ms-pulsar in a long-period LMXB cannot be adequately modelled.

7.3. *Spinning down the neutron star*

In the contex of the formation of ms-pulsars in long-period, transient LMXBs we should keep in mind that during the long-lasting quiescence phases the neutron star could also be spun down by the propeller effect (Illarionov & Sunyaev, 1975). A classical propeller, i.e. spin-down of the neutron star, results when during an accretion phase the mass flow rate through the disc drops so much that the magnetospheric radius $R_{\rm M}$ exceeds the corotation radius $R_{\rm co}$. Here the situation is different: In an outburst during which the neutron star is spun up, the inner radius of the disc is $R_{\rm i} \approx R_{\rm M,outb} \lesssim R_{\rm co}$, where $R_{\rm M,outb}$ is the magnetospheric radius for a (ststionary) disc in ouburst. Once the disc has gone in quiescence, its central parts, out to a radius $R_{\rm ev} \sim 10^{9.5}$cm, evaporate into an advection-dominated coronal accretion flow (Meyer & Meyer-Hofmeister, 1994), and the inner disc radius $R_{\rm i}$ is set by $R_{\rm ev}$ which is typically much larger than the magnetospheric radius in quiescence $R_{\rm M,qsc}$ calculated for the pressure of the coronal gas. Because for typical values of the parameters of the problem $R_{\rm M,qsc} \gg R_{\rm M,outb}$ the neutron star will be spun down during quiescence if it is spinning not too far below the equilibrium spin frequency corresponding to the outburst accretion rate. To what extent this spin-down is significant remains yet to be determined. Should it be significant then, depending on the initial conditions of a binary, this could even prevent the formation of a ms-pulsar.

Thus, spin-up of a neutron star to ms spin periods can occur if, on the one hand, the spin-down during the quiescence phases is not too large, and, on the other hand, either the neutron star magnetic moment is small (of order 10^{26}G cm^3) from the beginning, or decreases as a result of accretion, and the accretion efficiency is not too small. With ongoing spin-up the radius of the light cylinder $R_{\rm LC} = 4.8\ 10^9 {\rm cm} P_{\rm spin}(s)$ becomes eventually smaller than the inner radius of the disc in quiescence, i.e. $R_{\rm LC} < R_{\rm ev}$, and the corona becomes exposed to the pressure of the pulsar wind. With decreasing spin period the power of the pulsar wind $\propto \mu^2 {P_{\rm spin}}^{-4}$ grows, and one may ask whether at some point the pulsar wind is strong enough to blow away the evaporating coronal gas. A rough estimate using Eq. (17) of Meyer & Meyer-Hofmeister (1994) for the pressure of the coronal gas shows that this is indeed possible when the spin period drops below ~ 0.1s. Beyond that point the pulsar will no longer be spun down by the propeller effect during quiescence, and the spin-up process continues with higher efficiency.

From what has just been said it should have become clear that an adequate modelling of the spin history of a neutron star in a transient LMXB is a very demanding task which requires a proper treatment of the above-mentioned open problems.

8. Conclusions

In the foregoing sections we have discussed at some length the question whether irradiation is important for the secular evolution of LMXBs. Whereas there is clear observational evidence that irradiation does change the optical appearence of LMXBs (van Paradijs, 1994) and the properties of the outbursts in transient systems (e.g. King & Ritter (1998), Dubus, Hameury & Lasota (2001)), at present it is much less clear to what extent irradiation of either the outer parts of the accretion disc or the donor star influences the long-term evolution of LMXBs. The main reason for this is that a number of important problems which we have discussed in Sect. 7 need first to be solved.

The main effects which irradiation in a LMXB could have on its secular evolution are: 1) enhanced loss of mass and angular momentum from the system as a consequence of super-Eddington mass flow rates during the outbursts of transient LMXBs. This effect is more important for neutron star LMXBs than for black hole LMXBs. 2) For neutron star LMXBs the higher mass loss rates in an outburst mean that a lower fraction of the transferred mass is available for accretion onto the neutron star and thus for spinning it up. In this way irradiation makes it more difficult or even impossible for the neutron star to become a ms-pulsar. 3) Irradiation of the donor star can destabilize mass transfer and force the system to undergo irradiation-driven mass transfer cycles, i.e. an evolution which differs drastically from that expected without taking into account irradiation.

We have also seen that irradiation-driven mass transfer cycles could only occur in systems in which irradiation is sustained for a sufficiently long time, i.e. at least of order of the thermal timescale of the donor's convective envelope. Therefore, the occurrence of irradiation-driven mass transfer cycles is restricted to systems in which disc accretion is stable.

Finally we have seen that indirect irradiation by scattered accretion luminosity is probably needed (and also available) for irradiation-driven mass transfer cycles to work and, in transient LMXBs, for transforming an initially cool disc into a hot disc beyond the radius $R_{\mathrm{h,visc}}$ (cf. Eq. (1)).

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References

Büning, A, & Ritter, H., 2004, A&A 423, 281.
Dubus, G., Hameury, J.-M., Lasota, J.-P., 2001, A&A 373, 251.
Hameury, J.-M., Ritter, H., 1997, A&AS 123, 273.
Illarionov, A.F., & Sunyaev, R.A., 1975, A&A 39, 185.
King, A.R., Frank, J., Kolb, U., Ritter, H., 1996, ApJ 467, 761.
King, A.R., Kolb, U., Burderi, L. 1996, ApJ 464, L127.
King, A.R., Frank, J., Kolb, U., Ritter, H., 1996, ApJ 482, 919.
King, A.R., & Ritter, H., 1998, MNRAS 293, L42.
Lasota, J.-P., 2001, NAR 45, 449.
Liu, B.F., Meyer, F., & Meyer-Hofmeister, E., 1997, A&A 328, 247.
Meyer, F., Liu, B.F., & Meyer-Hofmeister, E., 2000, A&A 361, 175.
Meyer, F. & Meyer-Hofmeister, E., 1994, A&A 288, 175.
Podsiadlowski, Ph., 1991, Nature 350, 136.
Ritter, H., 1988, A&A 202, 93.
Ritter, H., 1999, MNRAS 309, 360.
Ritter, H., Zhang, Z.-Y., & Kolb, U., 2000, A&A 360, 969.
Ritter, H., & King, A.R., 2001, in: Evolution of Binary and Multiple Star Systems, eds. Ph. Podsiadlowski, S. Rappaport, A.R. King, F. D'Antona, & L. Burderi, ASP Conf. Ser., Vol. 229, 423.
van Paradijs, J., 1996, ApJ 464, L139.
Verbunt, F., & Zwaan C., 1981, A&A 100, L7.