A MULTI-FLOW MODEL FOR MICROQUASARS

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ABSTRACT

We present a new picture for the central regions of Black Hole X-ray Binaries. In our view, these central regions have a multi-flow configuration which consists in (1) an outer standard accretion disc down to a transition radius r_J, (2) an inner magnetized accretion disc below r_J driving (3) a non relativistic self-collimated electron-proton jet surrounding, when adequate conditions for pair creation are met, (4) a ultra relativistic electron-positron beam. This accretion-ejection paradigm provides a simple explanation to the canonical spectral states, from radio to X/γ-rays, by varying the transition radius r_J and disc accretion rate $\dot{m}$ independently. Some features such as possible hysteresis and the presence of quasi-periodic oscillations could be also described in this paradigm.

Key words: LaTeX; ESA; X-rays; Microquasars.

1. A NOVEL FRAMEWORK FOR BH XRBS

1.1. General picture

We assume that the central regions of BH XrB are composed of four distinct flows: two discs, one outer "standard" accretion disc (hereafter SAD) and one inner jet emitting disc (hereafter JED), and two jets, a non-relativistic, self-confined electron-proton MHD jet and, when adequate conditions for pair creation are met, a ultra-relativistic electron-positron beam. A sketch of our model is shown in Fig. 1 while the four dynamical components are discussed separately below (see also Ferreira et al. 2005, for more details). This is an extended version of the "two-flow" model early proposed for AGN and quasars (Pelletier et al., 1988; Sol et al., 1989; Pelletier & Roland, 1989; Henri & Pelletier, 1991; Pelletier & Sol, 1992) to explain the highly relativistic phenomena such as superluminal motions observed in these sources. This model provides a promising framework to explain the canonical spectral states of BH XrBs mainly by varying the transition radius r_J between the SAD and the JED. This statement is not new and has already been proposed in the past by different authors (e.g. Esin et al. 1997; Belloni et al. 1997) but our model distinguishes itself from the others by the consistency of its disc–jet structure and by the introduction of a new physical component, the ultra-relativistic electron-positron beam, that appears during strong outbursts. We believe that jets from BH XrBs are self-collimated because they follow the same accretion-ejection correlation as in AGN (Corbel et al., 2003; Fender et al., 2003; Merloni et al., 2003). This therefore implies the presence of a large scale vertical field anchored somewhere in the accretion disc (the JED) and we assume that this large scale B_z has the same polarity. The presence of a large scale vertical field threading the disc is however not sufficient to drive super-Alfvénic jets. This field must be close to equipartition as shown by Ferreira & Pelletier (1995) and Ferreira (1997). An important local parameter is therefore the disc mag-

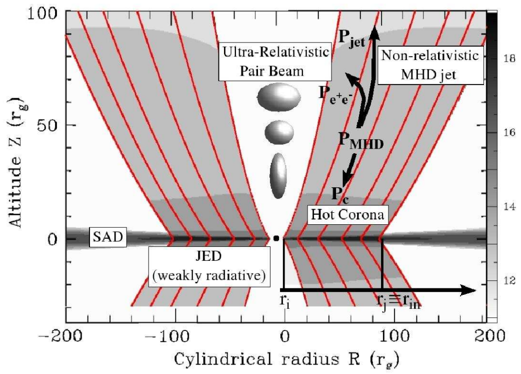

Figure 1. A Standard Accretion Disc (SAD) is established down to a radius r_J which marks the transition towards a low radiative Jet Emitting Disc (JED), settled down to the last stable orbit. The JED is driving a mildly relativistic, self-collimated electron-proton jet which, when suitable conditions are met, is confining an inner ultra-relativistic electron-positron beam. The MHD power P_{MHD} flowing from the JED acts as a reservoir for (1) heating the jet basis (radiating as a moving thermal corona with power P_c), (2) heating the inner pair beam ($P_{e^+e^-}$) and (3) driving the compact jet (P_{jet}). Field lines are drawn in black solid lines and the number density is shown in greyscale ($\log_{10} n/m^{-3}$). This magnetic accretion-ejection structure solution was computed with $\xi = 0.01$, $\varepsilon = 0.01$ and with $m = 10$ and $\dot{m}((r_J) = 0.01$ (see text).

netization $\mu = B_z^2/(\mu_o P_{tot})$ where P_{tot} includes the disc plasma and radiation pressures.

1.2. The outer SAD

We make the conjecture that a SAD no longer exists once μ reaches unity. It can be easily shown that one may reasonably expect μ to increase towards the center (Ferreira et al., 2005). Whenever a BH XrB reaches $\mu \simeq 1$ at a radius $r_J > r_i$, r_i being the last marginally stable orbit, the accretion flow changes its nature to a JED.

1.3. The inner JED

The inner region with $\mu \sim 1$ is fueled by the SAD at a rate $\dot{M}_{a,J} = \dot{M}_a(r_J)$. Since it undergoes mass loss, we parametrize the JED accretion rate following:$\dot{M}_a(r) = \dot{M}_{a,J}\left(\frac{r}{r_J}\right)^{\xi}$ where ξ measures the local ejection efficiency (Ferreira & Pelletier, 1993).

The dynamical properties of a JED have been extensively studied in a series of papers (see Ferreira 2002 and references therein). The ratio at the disc midplane of the jet torque to the turbulent "viscous" torque is

$$\Lambda \sim \frac{B_\phi^+ B_z/\mu_o h}{\alpha_v P_{tot}/r} \sim \frac{B_\phi^+ B_z}{\mu_o P_{tot}} \frac{r}{\alpha_v h} \quad (1)$$

It is straightforward to see that the necessary condition to drive jets (fields close to equipartition) from Keplerian discs leads to a dominant jet torque. In fact, it has been shown that steady-state ejection requires $\Lambda \sim r/h \gg 1$ (Ferreira, 1997; Casse & Ferreira, 2000). This dynamical property has a tremendous implication on the JED emissivity since it can be shown that the total luminosity of the JED is only a fraction $1/(1+\Lambda)$ of the accretion disc liberated power (Ferreira et al., 2005). In consequence, the JED is weakly dissipative while powerful jets are being produced regardless of the nature of the central object. As a consequence, the flux emitted by the JED is expected to be unobservable with respect to that of the outer SAD.

1.4. Non-relativistic electron-proton jets from JEDs

Although a large power is provided to the ejected mass (mainly electrons and protons), the mass loss (ξ) is never low enough to allow for speeds significantly relativistic required by superluminal motions: MHD jets from accretion discs are basically non or only mildly relativistic with $u_\infty \sim 0.1 - 0.8\,c$ (Ferreira, 1997). This is basically the reason why they can be efficiently self-confined by the magnetic hoop stress. Indeed, in relativistic flows the electric field grows so much that it counteracts the confining effect due to the toroidal field. This dramatically reduces the self-collimation property of jets (Bogovalov & Tsinganos, 2001; Bogovalov, 2001; Pelletier, 2004).

In our framework, jets from magnetic accretion-ejection structure (hereafter MAES) have two distinct spectral components detailed below:

- **A non-thermal extended jet emission:** We expect a small fraction of the jet power P_{jet} to be converted into particles, through first and/or second order Fermi acceleration, populating the MHD jet with supra-thermal particles. These particles are responsible for the bulk emission of the MHD jet. This is similar to models of jet emission already proposed in the literature (Falcke & Biermann, 1995; Vadawale et al., 2001; Markoff et al., 2001, 2003; Markoff, 2004; Falcke et al., 2004). In these models, the jet is assumed to be radiating self-absorbed synchrotron emission in the radio band (producing a flat or even inverted radio spectrum) becoming then optically thin in the IR-Optical bands and providing a contribution up to the X/γ-rays.

- **A thermal jet basis:** Jet production relies on a large scale magnetic field anchored on the disc as much as on MHD turbulence triggered (and sustained) within it. This implies that small scale magnetic fields are sheared by the disc differential rotation, leading to violent release of magnetic energy at the disc surface and related turbulent heat fluxes (e.g. Galeev et al. 1979; Heyvaerts & Priest 1989; Stone et al. 1996; Merloni & Fabian 2002). The energy released is actually tapping the MHD Poynting flux flowing from the disc surface. We can safely assume that a fraction f of it would be deposited at the jet basis, with a total power $P_c = fP_{MHD}$. The dominant cooling term in this optically thin medium is probably comptonization of soft photons emitted by the outer SAD (with a small contribution from the underlying JED). These are circumstances allowing a thermal plasma to reach a temperature as high as ~ 100 keV, (Pietrini & Krolik, 1995; Mahadevan, 1997; Esin et al., 1997). This plasma being at the base of the jet, it will have a vertical proper motion. Then its spectral behavior is expected to be close to that of a dynamic corona (Malzac et al., 2001).

1.5. The inner ultra-relativistic pair beam

Since the large scale magnetic field driving the self-confined jet is anchored onto the accretion disc which has a non zero inner radius, there is a natural hole on the axis above the central object with no baryonic outflow (this also holds for neutron stars). This hole provides a place for pair production and acceleration with the outer MHD jet acting as a sheath that confines and heats the pair plasma. This is the microquasar version of the "two flow" model that has been successfully applied to the high energy emission of relativistic jets in AGNs (Henri & Pelletier, 1991; Marcowith et al., 1995, 1998; Renaud & Henri, 1998).
The $e^+ - e^-$ plasma is produced by $\gamma - \gamma$ interaction, the γ-ray photons being initially produced by a few relativistic particles by Inverse Compton process, either on synchrotron photons (Synchrotron Self Compton or SSC) or on disc photons (External Inverse Compton or EIC). A key point of the two-flow model is that the MHD jet launched from the disc can carry a fair amount

of turbulent energy, most probably through its MHD turbulent waves spectrum. A fraction of this power can be transferred to the pairs ($P_{e^+e^-} << P_{MHD}$). Thus the freshly created pairs can be continuously reheated, triggering an efficient pair runaway process, leading to a dense pair plasma (Henri & Pelletier, 1991). In these conditions, the pair plasma will experience a strong bulk acceleration due to the recoil term of EIC, an effect also known as the "Compton Rocket" effect (O'Dell, 1981; Renaud & Henri, 1998). As shown in previous works, this "rocket" effect is the key process to explain relativistic motion (Marcowith et al., 1995; Renaud & Henri, 1998). For example, values of 5 to 10 can be easily reached in near-Eddington accretion regime around stellar black holes (Renaud & Henri, 1998).
Producing this pair plasma requires thus altogether a strong MHD jet, a radiative non-thermal component extending above the MeV range and a minimal $\gamma - \gamma$ optical depth, namely $\tau_{\gamma\gamma} \sim 1$ requiring high luminosity and small size systems (see Ferreira et al. 2005).

2. CANONICAL SPECTRAL STATES OF X-RAY BINARIES

2.1. The crucial roles of r_J and $\dot{m}$

From Section 1, it is clear that the spectral appearance of a BH XrB critically depends on the size of the JED relative to the SAD, namely r_J. As stated before, r_J is the radius where the disc magnetization $\mu = B_z^2/(\mu_o P_{tot})$ becomes of order unity. Thus, r_J depends on two quantities $P_{tot}(r,t)$ and $B_z(r,t)$. The total pressure is directly proportional to $\dot{m}$ since $P_{tot} = \rho\Omega_k^2 h^2 \propto \dot{m} m^{-1} r^{-5/2}$. As a consequence, any variation of the accretion rate in the outer SAD implies also a change in the amplitude of the total pressure. But we have to assume something about the time evolution of the large scale magnetic field threading the disc. The processes governing the amplitude and time scales of these adjustments of r_J to a change in $\dot{m}$ are far too complex to be addressed here. They depend on the nature of the magnetic diffusivity within the disc but also on the radial distribution of the vertical magnetic field. We will simply assume in the following that r_J and $\dot{m}$ are two independent parameters. In that respect, our view is very different from that of Esin et al. (1997); Mahadevan (1997) who considered only the dependency of $\dot{m}$ to explain the different spectral states of BH XrBs.

2.2. The Quiescent state

This state is characterized by a very low accretion rate ($\dot{m}$ as low as $\sim 10^{-9}$) with a hard X-ray component. The ADAF model has been successfully applied to some systems with a large transition radius between the ADAF and the outer standard disc, namely $r_{tr} \sim 10^3 - 10^4\ r_g$ (e.g. Narayan et al. 1996; Hameury et al. 1997). However, such a model does not account for jets and their radio emission, even though XrBs in quiescence seem also to follow the radio/X-ray correlation (e.g. Fender et al. 2003; Gallo et al. 2004, 2005). Within our framework, a BH XrB in quiescence has a large r_J, so that a large zone in the whole disc is driving jets (Fig. 2a). The low $\dot{m}$ provides a low synchrotron jet luminosity, while the JED is optically thin, producing a SED probably very similar to that of an ADAF. We thus expect $r_J \sim r_{tr}$. The weak MHD Poynting flux prevents the ignition of the pair cascade process and no pair beam is produced.

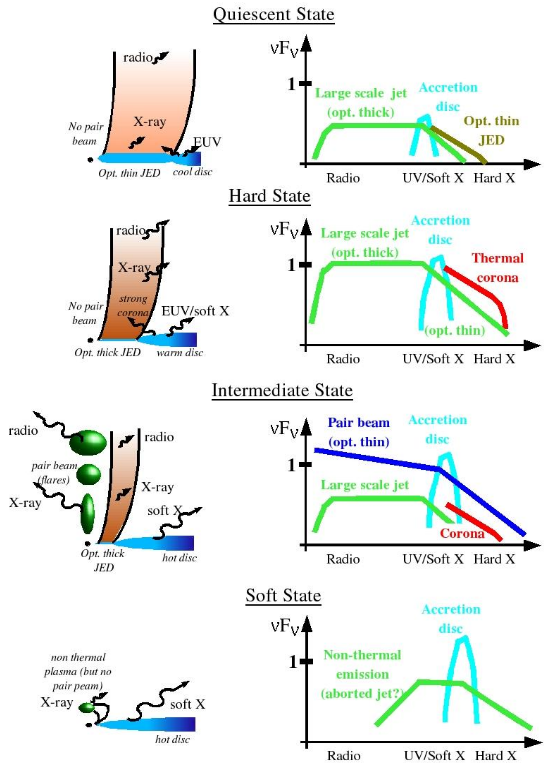

Figure 2. The canonical spectral states of X-ray binaries (cf. Sect. 2 for more details).

2.3. The Hard state

Within our framework, the JED is now more limited radially than in the Quiescent state, namely $r_J \sim 40 - 100\ r_g$ (Fig. 2b). This transition radius corresponds to the inner disc radius r_{in} as obtained within the SAD framework (Zdziarski et al., 2004). The low velocity of the plasma expected at the jet basis is in good agreement with recent studies of XrBs in Hard state (Maccarone, 2003; Gallo et al., 2003). It can also explain the apparent weakness of the Compton reflection (Zdziarski et al., 1999; Gilfanov et al., 1999) as already suggested by Markoff et al. (2003, see also Beloborodov 1999; Malzac et al. 2001) and tested by Markoff & Nowak (2004). In any case, the JED intrinsic emission is weak with respect to that of the outer standard disc: most of the accretion power flows out of the JED as an MHD Poynting flux. Nevertheless, the threshold for pair creation is still not reached and there is no pair beam, hence no superluminal motion. The MHD power is therefore shared between the jet basis, whose temperature increases (the thermal "corona") producing X-rays, and the large-scale jet seen as the persistent (synchrotron) radio emission.

2.4. The Soft state

Our interpretation of the Soft state relies on the disappearance of the JED, i.e. when r_J becomes smaller or equal to r_i (Fig. 2c). Depending on the importance of the magnetic flux in the disc, this may occur at different accretion rates. Thus, the threshold in $\dot{m}$ where there is no region anymore in the disc with equipartition fields may vary. The whole disc adopts therefore a radial structure akin to the standard disc model. Since no MHD jet is produced, all associated spectral signatures disappear. Even if pair production may take place (when $\dot{m}$ is large), the absence of the confining MHD jet forbids the pairs to get warm enough and be accelerated: no superluminal motion should be detected. Note also that the presence of magnetic fields may be the cause of particle acceleration responsible for the weak hard-energy tail (**?** hereafter McCR03, Zdziarski & Gierlinski 2003 and references therein).

2.5. Intermediate states

These states are generally observed during transitions between Hard and Soft states. Within our framework, they correspond to geometrical situations where r_J is small but remains larger than r_i (Fig. 2d). The flux of the outer standard disc is thus still important while the JED is disappearing. The consequences on the spectral shape are not straigtforward since the importance of the different spectral components relative to each other depends on the precise values of r_J and $\dot{m}$. Such study is out of the scope of the present paper and will be detailed elsewhere.

The crucial point however is that, in our framework, luminous intermediate states (the so-called Very High State or VHS) with high $\dot{m}$ provide the best conditions for the formation of the ultra-relativistic pair beam, as described in details in Sect. 1.5: (1) a high luminosity, (2) a high energy steep power law spectrum extended up to the γ-ray bands and (3) the presence of the MHD jet. The two first characteristics enable a $\gamma - \gamma$ opacity larger than unity, while the MHD jet allows to confine the pair beam and maintain the pairs warm, a necessary condition to trigger a pair runaway process. The total emission would be then dominated by the explosive behavior of the pairs, with the sudden release of blobs. Each blob produced in the beam first radiates in X and γ-ray, explaining the hard tail present in this state, and then, after a rapid expansion, produces the optically thin radio emission. This pair beam would also explain the superluminal ejections observed during this state in different objects (e.g. Sobczak et al. 2000; Hannikainen et al. 2001). We conjecture that the exact moment where this occurs corresponds to the crossing of the "jet line" recently proposed by Fender et al. (2004) (see also Corbel et al. 2004).

3. TIME EVOLUTION OF BH XRBS

The evolution with time of a BH XrB has been reported in Fig. 3 (Ferreira et al. in preparation). This is a synthetic Hardness–Intensity diagram (hereafter HID) as it is generally observed in XrBs in outbursts (e.g. Belloni et al. 2005; Fender et al. 2002, 2004). During such outbursts, the objects follow the A-B-C-D sequence before turning back to A at the end of the outburst. We detailed below the interpretation of this diagram in the framework of our model. We have also overplotted on Fig. 3 the different sketches of our model at different phases (this figure is clearly inspired by Fig. 7 of Fender et al. 2004).

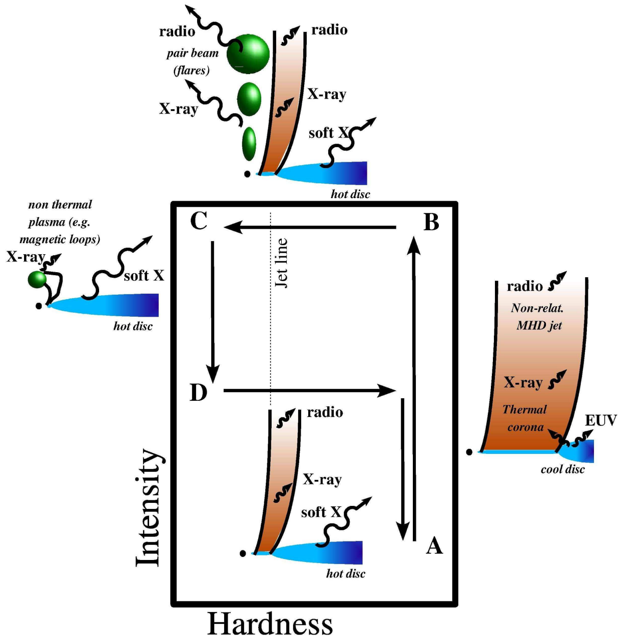

Figure 3. Schematic Hardness–Intensity diagram as it is generally observed in XrBs in outbursts (this figure is clearly inspired by Fig. 7 of Fender et al. 2004). During such outbursts, the objects follow the A-B-C-D sequence before turning back to A at the end of the outburst. The interpretation of this diagram within our framework is detailed in Sect. 3.

3.1. Ascending the Right Branch:

Let us start at a Low/Hard State located at the bottom of the HID right branch (in A in Fig. 3). In our view, such state would correspond to a JED extending up to typically $r_J \sim 10^2 r_g$. This considerably lowers the emission from the inner radii of the SAD producing a UV/soft X-ray excess. The hard (1-20 keV) power-law component of photon index $\Gamma \sim 1.7$ is attributed to the warm thermal plasma at the base of the jet. The non relativistic MHD jet then produces the persistent IR and radio synchrotron emission.

3.2. The Top Horizontal Branch

Before the jet line: Arriving in B we assume that r_J starts decreasing rapidly. Then, the MAES undergoes an outside-in transition to a SAD. The BH XrBs enter the high intermediate state. The flux of the outer standard disc then increases while the JED is decreasing. Under such circumstances, the MHD Poynting flux released by the JED is still important (through the large $\dot{m}$ that characterizes this part of the HID) but the MHD jet itself fills a smaller volume, a direct consequence being a weaker emission of the thermal "corona" and the non-thermal

MHD jet emission with respect to what it is while in the Hard state.

At the jet line: During its evolution along this top horizontal branch the system can reach a critical phase where the conditions for a strong pair production, inside the MHD jet structure, are fulfilled. In this case, we expect an explosive behaviour of the pairs, with the sudden release of blobs. The emission of these blobs, first in X and γ-ray and then, after a rapid expansion, in IR and radio, will probably dominate the broad band spectrum, producing the hard X-ray tail and the optically thin radio emission present in this state. The production of a series of blobs can even result in an apparently continuous spectrum, from radio to X/γ-rays. Remarkably, there is no evidence of steady radio jets during this phase but it is generally associated with radio and X-ray flares and/or superluminal sporadic ejections (e.g. Sobczak et al. 2000; Hannikainen et al. 2001). We note that the rapid increase of the pair beam pressure in the inner region of the MHD jet may dramatically perturb the MHD jet production and we expect a suppression of the steady jet emission when a large outburst sets in, in agreement with observations (Fender et al., 2004).

After the jet line: We assume that r_J is still decreasing. We therefore expect the total disappearance of the JED and its MHD jets when $r_J \rightarrow r_i$, thereby also causing the end of the pair beam (if present). The inner regions of the BHXB are a SAD with probably a magnetically active "corona". Indeed, it must be noted that the situation might be slightly more complex than a mere SAD because of the presence of a concentrated magnetic flux. No steady MHD ejection can be produced from the SAD but unsteady events could always be triggered. This is maybe the reason why this region in the HID seems to harbor complex variability phenomena (Belloni et al., 2005; Nespoli et al., 2003).

3.3. Descending the Left Branch

When XrBs reach the left vertical branch (point C in Fig. 3), r_J is smaller than the inner disc radius i.e. the JED and the MHD jet have completely disappeared. The whole disc adopts therefore a radial structure akin to the standard disc model and we enter into the so-called soft state (also called thermal dominant state McCR03) where the spectra are dominated by strong disc emission. The descent from C to D correspond to a decrease in intensity i.e. by a decrease of the accretion rate. This is the beginning of the fading phase of the outburst. In our framework r_J keeps smaller than r_i. We note also that we still expect the presence of magnetic fields that may be the cause of particle acceleration responsible for the weak hard-energy tail generally observed in this state (McCR03, ZG04 and references therein).

3.4. The Low Horizontal Branch

In D r_J begins to increase again. Thus, according to this conjecture, there is an inside-out build up of a JED. Self-collimated electron-proton jets could be produced right away. This means an increase of r_j, the reappearance of the non-thermal MHD jet and the thermal corona at its basis and a decrease of the SAD emission. But, contrary to the Top Horizontal Branch, the accretion rate is now too low to allow the production of a pair beam. Concequently we do not expect superluminal motions during this phase. When r_J reaches the same value as in the Low/Hard State the system is ready for another duty cycle.

4. SUMMARY AND CONCLUDING REMARKS

We present in this paper a new paradigm for the accretion-ejection properties of Galactic Black Hole X-ray binaries. We assume the existence of a large scale magnetic field of bipolar topology in the innermost disc regions. Such a field allows for several dynamical phenomena to occur whose relative importance determine the observed spectral state of the binary. The dynamical constituents are: (1) an outer standard accretion disc (SAD) for $r > r_J$, (2) an inner Jet Emitting Disc (JED) for $r < r_J$ driving (3) a self-collimated non-relativistic electron-proton surrounding, when adequate conditions are met, (4) a ultra-relativistic electron-positron beam. The dynamical properties of each constituent have been thoroughly analyzed in previous works (e.g. Shakura & Sunyaev 1973; Henri & Pelletier 1991; Ferreira & Pelletier 1995; Marcowith et al. 1997; Renaud & Henri 1998; Saugé & Henri 2003, 2004), but it is the first time where they are invoked altogether as necessary ingredients to reproduce the different spectral states of a same object. We showed that the various canonical states can be qualitatively explained by varying *independently* the transition radius r_J and the disc accretion rate $\dot{m}$.

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