Extreme luminosities in ejecta produced by intermittent outflows around rotating black holes

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ABSTRACT

Extreme sources in the Transient Universe show evidence of relativistic outflows from intermittent inner engines, such as cosmological gamma-ray bursts (GRBs). They probably derive from rotating back holes interacting with surrounding matter. We show that these interactions are enhanced inversely proportional to the duty cycle in advection of magnetic flux, as may apply at high accretion rates. We demonstrate the morphology and ballistic propagation of relativistic ejecta from burst outflows by numerical simulations in relativistic magnetohydrodynamics. Applied to stellar mass black holes in core-collapse of massive stars, it provides a robust explosion mechanism as a function of total energy output. At breakout, these ejecta may produce a low-luminosity GRB. A long GRB may ensue from an additional ultrarelativistic baryon-poor inner jet from a sufficiently long-lived intermittent inner engine. The simulations demonstrate a complex geometry in mergers of successive ejecta, whose mixing and shocks provide a pathway to broad-band high-energy emission from magnetic reconnection and shocks.

Key words: gravitational waves – stars: black holes – gamma-ray burst: general – stars: jets – supernovae.

1 INTRODUCTION

The Transient Universe reveals extreme relativistic sources with evidence for inner engines harbouring black holes. Foremost examples are cosmological gamma-ray bursts (GRB) associated with stellar mass black holes, the majority of which are long duration events believed to originate in aspherical supernovae (Papaliossis et al. 1989; Höflich, Wheeler & Wang 1999) within the larger class of core-collapse supernovae (CC-SNe; Maurer et al. 2010). It points to ajet-powered explosion mechanism (MacFayden & Woosley 1999) as a relativistic variant to a magnetic wind-powered explosion from an angular momentum rich inner engine (Bisnovatyi-Kogan 1970). While CC-SNe are fairly common, it should be mentioned that the branching ratio into LGRBs is quite small, at most a few per cent of the Type Ib/c supernovae (van Putten 2004; Guetta & Della Valle 2007). The mechanism for producing CC-SNe is therefore quite robust compared to producing a successful GRB. It is widely believed that a closely related mechanism produces relativistic outflows in their supernovae counterparts in active galactic nuclei (AGN).

Astrophysical black holes are generally rotating. According to the Kerr metric, they rotate fast than matter at the inner most stable circular orbit (ISCO) whenever the energy in angular momentum exceeds a mere 5.3 per cent of their maximal spin energy. Black holes have a remarkably broad window, therefore, for energetic interactions with and even on to surrounding matter via an inner torus magnetosphere (van Putten 1999, 2002). We expect a turbulent inner disc by competing torques from magnetic surface stresses, i.e., by feedback from the black hole and outgoing winds, shaping it into a torus by induced thermal and magnetic pressure.

Extremely luminous GRBs further show burst-like behaviour in outflows from a possibly intermittent inner engines, providing the conditions for recurrent shocks in relativistic outflows in the internal shock model of the prompt gamma-ray emission in GRBs (Rees & Mészáros 1994; Kobayashi, Piran & Sari 1997; Levinson & van Putten 1997; Piran & Sari 1997; Daigne & Mochkovitch 1998; Fenimore, Ramirez-Ruiz & Wu 1999).

Long GRBs from the Burst and Transient Source Experiment (BATSE; Kouveliotou et al. 1993) show a pronounced positive correlation between luminosity in variability (Stern, Poutanen & Svensson 1999; Reichart et al. 2001). Possibly related is the more recently discovered Swift class of short GRBs with Extended Emission (SGRBEE) and long GRBs with no association with supernovae (LGRBN). Their long/soft tails share the same Amati correlation as normal LGRBs but with relatively small isotropically equivalent energies ($E_{iso}$), perhaps as a result of their different astronomical origin (van Putten et al. 2014). Microquasars such as GRS 1915+105 (Mirabel & Rodríguez 1994) and quasars such as 3C 273 and 3C 279 (Pearson et al. 1981; Wehrle et al. 2001) are well known for their extreme luminosities and blobs appearing at superluminal velocities (e.g. Antonucci 2013). Conceivably, they share a similar emission mechanism, whose luminosity is somehow
enhanced by intermittency in the inner engine. In particular, the interaction of a black hole on to matter at the ISCO may be inherently unstable or unsteady, e.g. by superradiant scattering (van Putten 1999), hydrodynamic or magnetic-pressure-induced instabilities (van Putten & Levinson 2003), accretion from an inhomogeneous disc (Dexter & Algol 2011) or otherwise. These intermittencies will result in burst outflows in magnetic winds from an inner disc or torus winds, possibly along with burst outflows in ultrarelativistic jets along the black hole spin axis.

Here, we ask: Is luminosity enhanced by intermittency, circumventing bounds that may exist in the more restricted class of steady-state models? To this end, we consider the luminosity and morphology of burst-like outflows in magnetic disc or torus winds as a function of duty cycle, defined by the ratio of the duration \( \tau \) of the on-state to a (quasi-)periodic \( T \) of the on- and off-state, and accretion rate, as a boundary condition to an extended accretion disc.

The luminosity of magnetic winds derives from poloidal magnetic flux by Faraday induction, whereas their total energy output derives from accretion and, possibly, the spin energy of a central black hole. Hyper-accretion in core-collapse of massive stars (Woosley & Weaver 1986) may advect magnetic flux, leading to build up of potentially strong magnetic flux around the black hole as a function of accretion rate (cf. Kumar, Narayan & Johnson 2008). Alternatively, feedback from the black hole may power a dynamo in matter about the ISCO. Strong magnetic fields may develop even in the absence of accretion, e.g. in mergers of neutron stars with another neutron star or black hole companion. Either way, the energy in the poloidal magnetic field is subject to a stability limit in quasi-stationary models (van Putten & Levinson 2003).

In what follows, we use the theory of relativistic ideal magnetohydrodynamics (RMHD). RMHD is well suited for studying outflows from compact sources by their large hydrodynamical and magnetic Reynolds numbers. It contains fast and slow magnetosonic waves as well as Alfvén waves. For rotating systems, Alfvén waves are crucial to shedding angular momentum in magnetic winds along helical magnetic fields that may extend, if open, out to infinity. Exposed to a poloidal magnetic field from an inner accretion disc, a rotating black hole develops an equilibrium magnetic moment that may similarly support open magnetic field lines out to infinity. Subject to frame dragging, measured around the Earth (Ciufolini & Pavlis 2004; Everitt et al. 2011), blobs of charged particles can be ejected in their radiative Landau states by a powerful spin–orbit coupling resulting from Papapetrou forces (Papapetrou 1951; van Putten 2005, 2008), likewise shedding angular momentum to infinity.

Crucial to the formation of magnetized outflows are the conditions at launch, and mostly so at the inner disc down to the ISCO where the disc luminosity in winds is largest (Lovelace et al. 2002; Lovelace & Romanova 2003). Away from shocks, ideal MHD describes the adiabatic evolution of a magnetized fluid. Non-equilibrium pressure conditions at launch hereby tend to propagate along with the outflow downstream, allowing distinctive complex time-dependent jet morphology to develop throughout the life of the jet. In addition to the distinctive nose-cone of toroidally magnetized jets marking the head of the jet (Clarke, Norman & Burns 1986; Lazatti et al. 2012), these conditions can produce magnetized toroidal vorticity (MTV, in the shape of a shoulder) propagating at intermediate velocity (van Putten 1996). The MTV-nose cone morphology is a sharp departure from hydrodynamical jets, where a hydrodynamical toroidal vorticity (HTV) marks the head of the jet. It represents back flow forming a cocoon of shocked jet flow in its wake, that envelopes the unshocked jet.

We now argue that intermittencies at the source of outflows are advantageous to the launch of powerful winds. In transverse MHD, poloidal flux is advected in proportion to mass accretion rate, \( \dot{m}(t) \). Since associated instantaneous luminosity \( L_{\text{iso}}(t) \) in magnetic winds scales with the square of poloidal magnetic flux, we have \( L_{\text{iso}} \propto \dot{m}^2(t) \). Given a duty cycle defined by a typical duration \( \tau \) of bursts repeated over intervals of order \( T \); we obtain (van Putten & Wilson 1999)

\[
\langle L_{\text{iso}} \rangle = \frac{4}{3} \frac{L_{\text{iso}}}{T} \left( \frac{T}{\tau} \right).
\]

where the superscript \( \text{i} \) refers to the intermittent luminosity and \( c \) refers to the equivalent continuous luminosity at a given mean mass accretion rate \( \dot{m}_0 \) far out in the extended accretion disc.

The result (1) follows from scaling of luminosity in Poynting flux \( L = k_1 \Phi^2 \), where \( \Phi \) denotes the poloidal magnetic flux advected to the ISCO and \( k_1 \) represents remaining parameters such as angular velocity in the underlying Faraday induction process. In the presence of, e.g., violent instabilities in the inner accretion disc or torus, the mass \( m(t) \) about the ISCO satisfies \( m(t) = \alpha t (0 \leq t \leq \tau) \) in the on-state and \( m(t) = 0 \) \((\tau < t < T) \) in the off-state. Here, \( \tau/T \) is the duty cycle and \( \alpha \) is the instantaneous mass accretion rate on to the ISCO. In advecting \( \Phi \) by \( m \), \( \Phi = k_1 m \) for some constant \( k_1 \), whereby \( L = km^2 \) with \( k = k_1 k_2 \). Here, \( k \) will be effectively constant over intermittent time-scales \( T \) much less than the lifetime of the source. Accordingly, the mean mass about the ISCO satisfies

\[
\langle m \rangle = \frac{1}{T} \int_0^T \dot{m}(t) dt = \frac{\alpha}{2} \frac{T^2}{\tau^2} \label{eq:m}
\]

with associated mean luminosity

\[
\langle L_{\text{iso}} \rangle = \frac{k}{T} \int_0^T \dot{m}(t) dt = \frac{k \alpha^2 \tau^3}{3 T} = \frac{4}{3} k < m \geq T \frac{T}{\tau} \label{eq:Liso}
\]

Identifying \( L_{\text{iso}} = k \langle m \rangle^2 \) with the luminosity that would be produced by the mean mass at the ISCO, equation (1) follows.

To exemplify, the microquasar GRS 1915+105 has \( T/\tau \) of the order of 60. At this (inverse) duty cycle, equation (1) shows that intermittencies can enhance the power output by well over an order of magnitude over that of a steady-state source at the same accretion rate. It is tempting to speculate that at least some of the anomalously large luminosity in its supermassive counterparts such as the quasar 3C 273 can similarly be attributed to an appreciable duty cycle, apparent in the ejection of relativistic blobs at a minimum Lorentz factor \( \Gamma = \sqrt{1 + \beta_\perp^2} \approx 10 \), where \( \beta_\perp \approx 9.6 \) denotes their apparent velocities on the celestial sphere. The same such intermittencies also appear to be advantageous to emitting Ultra-High Energy Cosmic Rays from on-average low-luminosity AGN (Farrar & Gruzinov 2009; van Putten & Gupta 2009).

In the propagation of Alfvén waves downstream and outside of light cylinder of a central engine, open magnetic winds inevitably become toroidal (Contopoulos 1995). Simulations demonstrate that toroidal magnetization gives rise to the aforementioned distinctive nose-cone, by which the head of the jet propagates relatively fast compared to unmagnetized jets (Clarke et al. 1986; van Putten 1996). In three-dimensions, simulations show that toroidally magnetized jets are not threatened by the kink instability (McKinney & Blandford 2009). Magnetized toroidally magnetized outflows hereby appear to be a suitable starting point to address the ubiquity of jet-driven supernovae from intermediate to relatively massive stellar progenitors, and principally different from relativistic hydrodynamics.
Figs 1 and 2 show the morphological evolution, propagation and breakout from a remnant stellar envelope of ejecta from burst outflows employing a fully four-covariant hyperbolic system of Maxwell’s equations in divergence form (van Putten 1991, 1993, 1994) in the approximation of axisymmetry.

Fig. 1 shows the formation of a relativistic ejecta following a burst of low-density outflow into a stellar interior of relatively high density, modelled by an aperture with time-dependent boundary conditions. Out-of-equilibrium radial pressure due to magnetic pinch at launch produces a characteristic MTV-nose cone morphology. The Mach disc in the latter is generally unsteady which tends to shed internal sonic nozzles in its wake, that appear as knotted structures. The results of the burst outflow, in distinction to continuous outflow, is a ballistically propagating nose cone, after the MTV dissolved by an expansion wave. At moderate Lorentz factors, the expansion wave following switch off can even appear as back flow to the source.

The numerical simulation demonstrates the formation ejecta disconnected from the source, that live long after switch off of the engine. They ultimately escape through a successful breakout into the surrounding region of relatively lower density. In our model, the velocity of sound in the corona just outside the star is larger than inside, giving rise to a distinguishable relativistic expansion in the stellar corona at breakout of the nose-cone. Any high-energy emission from the breakout process hereby may derive from both the relativistic Mach disc inside the head as well as from this large area and wide angle relativistic bow shock.

The formation of a nose-cone as stable ejecta is unique to magnetized outflows, not found in hydrodynamical simulations. Switching off a hydrodynamical jet results in dissolving the HTV at the head, leaving only a large angle bow shock that may produce a non-relativistic supernova with no high-energy emissions at breakout (Lazzati et al. 2012). Relevant to breakout of magnetized ejecta, therefore, is their total energy rather than the lifetime of the inner engine. These ejecta hereby provide a robust explosion mechanism that is remarkably insensitive to the details of the source.

The aspherical CC-SNe with LGRBs and low luminosity GRBs (LLGRBs) such as GRB 980425/SN1998bw (Galama et al. 1998) are commonly attributed to the breakout of the bow shock ahead of a relativistic wind or jet. Relativistic shocks at breakout have been associated with the smooth light curves of LLGRBs, e.g. GRB 980425/SN1998bw, GRB060218/SN1006aj (Campana et al. 2006) and GRB080109/SN2008D (Mazzali et al. 2008; Soderberg et al. 2008), here attributed to the breakout of moderately relativistic magnetized ejecta from the inner accretion disc around a rotating black hole. Disk winds and their ejecta hereby provide an efficient aspherical explosion mechanism with and without association with GRBs (Maeda, Mazzali & Nomoto 2006; Taubenberger et al. 2009), that may be especially efficient when baryon rich (van Putten, Della Valle & Levinson 2011).

In extreme cases, outflows discs may collimate an ultrarelativistic baryon-poor jet from a rapidly rotating black hole. Ultrarelativistic baryon-poor outflows provide just the kind of agent needed to successfully produce a normal long GRBs. Their prompt GRB emission is believed to result from internal shocks, converting kinetic energy into non-thermal radiation possibly augmented by dissipation of magnetic fields. Intermittency at the source then appears necessary for producing strong internal shocks downstream, here enhanced by intermittency following (1). Long-duration GRB-supernovae hereby result from rare instances of two component outflows, from an ultrarelativistic baryon-poor inner jet within baryon-rich winds or ejecta powering the supernova (e.g. van Putten & Levinson 2003).

For intermittencies derived from random processes, we next turn to two outbursts with toroidal field reversal.

Fig. 2 shows the interaction of two ejecta and the subsequent partial mixing of their toroidal magnetic fields, as the second gradually overtakes and mergers with the first. This mixing is advantageous towards reconnection of the toroidal magnetic field (e.g. Lyutikov & Blandford 2003), which is otherwise hard to attain in planar shocks from otherwise similarly intermittent sources (Levinson & van Putten 1997).

Although this experiment is shown for moderately relativistic ejecta appropriate for baryon-rich disc winds, we advance the notion of magnetic reconnection by mixing in the merger of relativistic ejecta with random orientation of magnetic fields at work also in ultrarelativistic outflows. Orientation reversal in magnetic fields then results from the aforementioned turbulent inner disc or...
torus around a rotating black hole. Since normal LGRBs require a two-component jet, while LLGRBs may already result from a baryon-rich disc wind, the latter is naturally more rare than the former. The associated stellar explosion may result from both. This explains the robustness of CC-SNe and may explain the different branching ratios into LLGRBs and normal LGRBs.

By equation (1), Figs 1 and 2, we propose a paradigm shift for the most extreme sources to be inherently burst-like. Their luminosity is enhanced by intermittency at the source by the inverse of the duty cycle, which gives rise to ballistic ejecta. Merging of these ejecta with randomly oriented magnetic fields leads to naturally to mixing and shocks. Applied to ultrarelativistic outflows, it provides a pathway to a broad-band spectrum (Giannios 2012; Levinson 2012; Beloborodov 2013; Yurik, Lyubarsky & Piran 2013; Keren & Levinson 2014) from magnetic reconnection (Drenkhahn & Sprint 2002; Lyutikov & Blandford 2003; Giannios & Spruit 2005; McKinney & Uzdensky 2012) and shock acceleration of, respectively, MeV to GeV photons (Stern 1999), provided that the reconnection rate is sufficiently high at sufficient entropy (Lyubarsky 2005, 2010). A detailed analysis thereof falls outside the scope of the present numerical demonstration on the complex geometry of merging ejecta in RMHD.

Our mechanism for creating extremely luminous outflows seems particularly applicable to the most powerful normal LGRBs associated with hyperenergetic supernovae such as GRB 031203/SN2003lw (Malesani et al. 2004) and GRB 030329/SN2003dh (Hjorth et al. 2003; Matheson et al. 2003; Stanek et al. 2003). Without an ultrarelativistic inner jet, the relativistic expansion of the outer layers of the stellar remnant envelope at breakout of the moderately relativistic ejecta of Figs 1 and 2 may account for the relatively more numerous LLGRBs (Kulkarni et al. 1998), closely related to the original proposal of Colgate (1968, 1970, 1974).

Normal long GRBs are distinct from the aforementioned less extreme Swift class of SGRBEE and LGRBNs exemplified by GRB 050724 (Berger 2005; Barthelmy 2007) and, respectively, GRB 060614 (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006). The latter may originate in mergers, e.g. of two neutron stars, producing low-mass black holes with rapid spin (Baiotti, Giacomazzo & Rezzolla 2008). The distinct $E_{\text{out}}$ from normal LGRBs on the one hand and SGRBEE and LGRBNs on the other hand may result from, respectively, hyperaccretion in CC-SNe and limited accretion in mergers: hyperaccretion on to the ISCO may destabilize the torus and the inner torus magnetosphere, pushing it to intermittency and hence enhanced luminosities by equation (1).

Our RMHD simulations show several distinctive features over hydrodynamical jets: (a) enhanced luminosity by intermittency; (b) intermittency producing long-lived magnetized ejecta (Fig. 1) that may power relativistic aspherical explosions without requiring a long-lived continuous inner engine; (c) intermittency from turbulent engines producing merging ejecta with randomly oriented magnetic fields (Fig. 2), whose reconnection would provide additional energy to high-energy emissions in internal shocks.

Latent accretion on the remnant inner engine has recently been considered to explain flaring, prevalent post-long-GRB emission (Chincarini et al. 2010), possibly from fall-back of matter from an outer envelope of the progenitor star at reduced accretion rates (e.g. $\dot{m}(t) \propto t^{-3}$ in Kumar et al. 2008). In our model, this accretion tail falls on to slowly rotating black holes following spin-down. With no feedback, the black hole luminosity is expected to scale linearly in $\dot{m}$ at low efficiency (McKinney 2005). Inhomogeneous accretion flows due to cooling (e.g. Gammie 2001; Mejia et al. 2005; Rice, Lodato & Armitage 2005) hereby may produce low-luminosity flaring for an extended period of time.

As energetic and catastrophic events involving rapidly rotating high-density matter, aspherical supernovae are candidate sources of gravitational waves. This output would extend for the lifetime of the inner engine, i.e. long from normal GRB-SNe and possibly short or long from LLGRBs. Due to its proximity, the inner disc of SgrA* might similarly be a persistent source of gravitational radiation of interest to future space-based gravitational wave detectors.

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