Powerful non-thermal emission in black-hole powered sources

V. Bosch-Ramon

(1) Max Planck Institut für Kernphysik

Abstract.
Powerful non-thermal emission has been detected coming from relativistic collimated outflows launched in the vicinity of black holes of a very wide range of masses, from few to $\sim 10^{10} M_\odot$. These collimated outflows or jets have large amounts of energy and momentum extracted from the black hole itself and/or from matter trapped in its potential well. The key ingredients for the formation of these powerful jets are accretion of matter with angular momentum, the huge gravitational potential of the compact object, the strong ordered magnetic fields near the black-hole horizon, the potentially large rotational energy in the case of a Kerr black hole, and an escape velocity close to $c$. At different scales along the outflows, i.e. $\sim 10^{-10^{10}} R_{\text{Sch}}$ from the black hole, the local conditions can lead to the generation of non-thermal populations of particles via, e.g., magnetic reconnection, magneto-centrifugal mechanisms, diffusive processes, or the so-called converter mechanism. These non-thermal populations of particles, interacting with dense matter, magnetic, and radiation fields, could yield radio-to-gamma-ray emission via synchrotron process, inverse Compton scattering, relativistic Bremsstrahlung, proton-proton and photo-hadron collisions, and even heavy nuclei photo-disintegration. Other processes, like pair creation or the development of electromagnetic cascades, could be also relevant in black-hole jets and their surroundings. Black holes of different masses, accretion rates and environments show different phenomenologies, as can be observed in AGNs, GRBs or microquasars. Nonetheless, these sources basically share the same fundamental physics: accretion, black-hole rotation, plus an environment, but they are individualized due to their own specific conditions. In this paper, we qualitatively review the main characteristics of the non-thermal emission produced in jets from black holes, giving also a brief overview on the physical properties of black hole/jet systems. We comment as well on some important differences and similarities between classes of sources, and on the prospects for the study of the non-thermal emission from astrophysical sources powered by black holes.

Resumen.
En las cercanías de agujeros negros de un amplio rango de masa, $\sim 1 - 10^{10} M_\odot$, se eyectan poderosos chorros relativistas de plasma que producen emisión no térmica. Estos chorros pueden transportar grandes cantidades de energía y momento extraídos del agujero negro y/o de la
matería atrapada en su pozo gravitacional. Para la formación de estos chorros de plasma, los ingredientes clave son la acreción de materia con momento angular, el intenso potencial gravitacional del agujero negro, la presencia de fuertes campos magnéticos ordenados, la posiblemente gran energía rotacional del agujero negro, y la alta velocidad de escape, que puede ser cercana a $c$. A diferentes escalas espaciales de los chorros de plasma, a $\sim 10^{-10} R_{\text{Sch}}$ del agujero negro, las condiciones locales pueden llevar a la generación de poblaciones no térmicas de partículas via reconexión magnética, un mecanismo magneto-centrífrugo, procesos difusivos, o el llamado mecanismo de conversión. Estas poblaciones no térmicas de partículas, interactuando con densos campos de radiación, magnéticos, y de materia, dan lugar a emisión de fotones de muy diferentes energías por radiación sincrotrón, dispersión Compton inverso, Bremsstrahlung relativa, colisiones protón-protón, y foto-desintegración de núcleos atómicos pesados. Otros procesos, como creación de pares electrón-positrón, o el desarrollo de cascadas electromagnéticas, podrían ser también relevantes en estos chorros y en sus inmediaciones. Agujeros negros de diferentes masas y medios circundantes mostrarán diferentes fenomenologías, como ocurre con los núcleos de galaxias activas, las explosiones de rayos gamma, o los microcuásares, que son fuentes que comparten básicamente la misma física fundamental: acreción, agujero negro en rotación, y un medio circundante, aunque con importantes diferencias específicas. En este trabajo, se discuten a nivel cualitativo las características más significativas de la emisión no térmica proveniente de chorros lanzados por agujeros negros, y se resumen brevemente las propiedades físicas de este tipo de objetos. También se consideran las principales diferencias y similitudes entre clases de fuentes, y se comentan las perspectivas del estudio de la emisión no térmica en fuentes con agujeros negros.

1. Introduction

There is very strong observational evidence for the existence of black holes. From the epoch of the discovery of the X-ray source Cygnus X-1 as a binary system likely harboring a black hole (Bolton 1972; Webster & Murdin 1972), to the present days, the number of black hole candidates has grown substantially at stellar as well as at super massive scales (e.g. Casares 2001; Schödel et al. 2002). In general, among other methods, evidence for a black hole comes from observations giving dynamical information on the mass of the object under study, since compact objects more massive than black holes are not expected for certain masses ($M > 3 M_\odot$ for stellar mass objects; e.g. Casares 2001; see also Paredes 2008a). Lower mass black holes could also exist, although to find them we are constraint by our present knowledge on the physics of the collapsed object material. Hereafter, we will assume that black holes do exist, and discuss how they could be involved in very energetic and luminous events in the Universe. We will focus our study on the production of non-thermal radiation, which is strongly linked to the generation of jets.

The deep potential well of black holes can allow to release large amounts of potential and rotational energy to the infinity (e.g. Lynden-Bell 1969; see also...
Since several decades ago (e.g. Burbidge 1956), it has been known that non-thermal emission is generated in the jets produced in compact objects. In these jets, non-thermal populations of particles (or cosmic rays -CRs-) are generated and can interact with dense matter, magnetic, and radiation fields. Leptonic and hadronic processes associated with these interactions yield radiation from radio to gamma-rays, and also neutrinos. The electromagnetic emission, as well as neutrinos and CRs, can be observed with instruments, either ground or space based, working in very different spectral domains, covering almost 30 orders of magnitude in energy, from $\sim 10^{-6}$ to $10^{22}$ eV (i.e. from radio up to ultra high-energies -UHE-). There are basically three known classes of sources that harbor black holes and are powerful non-thermal emitters: Active Galactic Nuclei (AGNs), Gamma-Ray Bursts (GRBs) and microquasars (MQs) (e.g. Begelman et al. 1984; M´ esz´ aros 2006; Mirabel & Rodr´ ıguez 1999). All these sources basically share the same fundamental physics, although show distinct spectral, spatial and temporal behavior due to their own specific characteristics. In this paper, we qualitatively discuss the main features of the non-thermal emission of jets, ejected from the vicinity of black holes, trying to give at the same time a very brief overview on the physical properties of these objects. We also comment on what are the main differences and similarities between classes of sources, and on the prospects for the study of non-thermal emission in black-hole powered sources. It is not intended to discuss here neither observations nor theory of these objects, thus we refer to the cited works where relevant observational and theoretical references can be found. Also, it is noted that the brief overview presented here does not intend to be exhaustive, but just touch in a simple manner the different concerned topics.

For illustrative purposes, we present in Fig. 1 an example of jets associated with a black-hole powered source.

2. Non-thermal radiation from black holes

2.1. The black-hole engine

Black holes are regions of the spacetime separated from the rest of the Universe by an event horizon, which is a closed surface in which all the light cones point towards inside the black hole. This implies that no matter, nor signal, can propagate outwards from this surface. The existence of this surface is caused by the...
presence of matter and fields inside the horizon with an energy-momentum large enough as to produce such a distortion of the metric of the space-time or, put in different words, to create such a large gravitational potential that even massless particles cannot escape. Black holes are described by the solutions of the Einstein equations of the general relativity (Einstein 1915) that represent a collapsed object (see Romero 2008a for a recent review). In the context of general relativity, black holes are described by just three quantities: mass, angular momentum, and charge, and the metric describing the different types of black hole are the Schwartzschild’s metric (massive; Schwarzschild 1916a, 1916b); Kerr’s metric (massive and rotating; Kerr 1963); Reissner-Nordström’s metric (massive and charged; Reissner 1916, and Nordström 1918); and Kerr-Newmann’s metric (massive, rotating and charged; Newmann et al. 1965). As already mentioned and explained further in the following sections, the deep gravitational potential of a black hole allows accretion to be a very efficient energy source, and the same for the rapid rotation of a Kerr black hole. The energy is finally released in the form of electromagnetic radiation, CRs and neutrinos, making of black holes the powerful engines of the brightest objects in the Universe.
2.2. Accretion and jet formation

Accretion of matter can render the conditions for the generation of powerful jets. The energy required to launch these jets is extracted either from the accreted matter itself (e.g. Blandford 1976; Lovelace 1976; Blandford & Payne 1982), or from the rotation of the black hole (e.g. Blandford & Znajek 1977; Punsly & Coroniti 1990).

Once the material filling the nearby regions start to fall towards the black hole, its angular momentum makes it to move along Keplerian orbits preventing it from reaching the event horizon. To allow the material to get closer to the black hole, the angular momentum must be redistributed, which requires some release of kinetic energy that can be done via viscous friction (e.g. Shakura & Sunyaev 1973; see also Lynden-Bell & Pringle 1974) or some kind of wind or collimated outflow/jet (e.g. Bogovalov & Kelner 2008). In this way, matter can reach the innermost part close to the horizon.

In the context of dissipative accretion disks, the magneto rotational instability (MRI; see, e.g., Balbus & Hawley 1998) is presently the best candidate to yield the conditions for efficient accretion and subsequent magnetic dominated jet formation and collimation (e.g. Beckwith et al. 2008). The MRI mechanism would play the role of the phenomenological viscosity introduced by Shakura & Sunyaev (1973), and would lead to the formation of the ordered magnetic fields in the inner accretion disk regions required for jet launching (e.g. Kato et al. 2004; Fragile 2008). Concretely, for the case of a rotating black hole, the amplified magnetic field gets strongly bent by the material moving in the ergosphere, generating Alfven waves that carry angular momentum and energy taken from the rotational energy of the compact object (e.g. Koide et al. 2002; Barkov & Komissarov 2008), although differential rotation of the accretion disk alone can also lead to jet production (e.g. Lynden-Bell 1996).

2.3. Outflows and particle acceleration

Supersonic jets are observationally and theoretically linked to the production of non-thermal emission. The kinetic energy associated with the jet matter motion can be converted into non-thermal particle energy via acceleration through different mechanisms. The most common mechanism in many astrophysical situations is diffusive or Fermi-I shock acceleration (e.g. Bell 1978a, 1978b; Drury 1983), which would take place in AGNs, GRBs and MQs for instance in the internal shock scenario for the production of high-energy emission (e.g. Rees 1978; Kobayashi et al. 1997; Kaiser et al. 2000), and also at the shocks produced when jets terminate in the external medium (e.g. Blandford & Rees 1974; Mészáros & Rees 1997; Heinz & Sunyaev 2002). Another candidate for accelerating particles in jet regions where the magnetic field is relatively high and turbulent is the Fermi-II type acceleration mechanism (e.g. Fermi 1949), and under the presence of significant velocity gradients, shear acceleration (e.g. Berezhko & Krymskii 1981; Rieger & Duffy 2004). Fermi-II and shear acceleration may be behind the emission at intermediate scales, in regions where faint and extended radiation is produced. A discussion of the occurrence of these three acceleration processes in AGNs, GRBs, and MQs can be found in Rieger et al. (2007).

In general, the acceleration of particles requires two mediums with relative velocity (or one medium with a velocity gradient), and/or some sort of scattering
centers (e.g. magnetic inhomogeneities) moving isotropically in each medium. Particles cross the separation, a shock or velocity gradient region, between the two mediums, as in the case of Fermi-I and shear acceleration, and/or get scattered in the moving centers, as in the case of Fermi-II acceleration. In these two ways, particles gain energy with each forth-and-back shock crossing, and with the accumulative effect of many center scatterings. We note that the scattering centers are required also for Fermi-I acceleration since particles have to cross the discontinuity several times. For this, particles are deflected by these centers and redirected towards this surface after each crossing. Actually, as discussed in Rieger et al. (2007), the three mechanisms discussed above, Fermi-I, Fermi-II and shear, could compete in the same source.

When very fast outflows are involved, and under very dense radiation fields, the converter mechanism can be efficient for electrons, and protons (e.g. Derishev et al. 2003; Stern & Poutanen 2006). In this mechanism, particles suffer interactions with the photons of the intense radiation field and channel most of their energy to a neutral particle, a photon (for electrons) or a neutron (for protons). These conversions can allow acceleration to become extremely efficient, challenging even the classical electrodynamical limit (Hillas 1984). Very close to the black-hole horizon, particles could be also accelerated by magnetocentrifugal forces, like in the pulsar magnetosphere (e.g. Neronov & Aharonian 2007; Rieger & Aharonian 2008). Finally, magnetic reconnection (e.g. Romanova & Lovelace 1992; Zenitani et al. 2001) could also accelerate particles in some specific situations, namely in the regions where the magnetic field is expected to be dynamically dominant, e.g. in the base of the jet. In this process, field lines of opposite polarity that get very close suddenly connect to each other, heating the plasma and accelerating particles.

2.4. Types of sources

The main source types that harbor black holes and produce non-thermal emission are: AGNs, which are galaxies harboring an actively accreting supermassive ($\sim 10^6 - 10^{10} \, M_\odot$) black hole and can produce non-thermal emitting relativistic outflows (e.g. Begelman et al. 1984; Rees 1984; Osterbrock 1993); GRBs (e.g. Mészáros 2006), which would result from the collapse of a very massive star or from the coalescence of two neutron stars or a neutron star and a black hole (e.g. Eichler et al. 1989; Woosley 1993; Paczynski 1998), yielding long and short GRBs (Kouveliotou et al. 1993); and MQs, which are X-ray binaries with relativistic jets (e.g. Mirabel & Rodríguez 1999; Ribó 2005; Fender 2006).

In all these three kinds of object, AGNs, GRBs, and MQs, the site of non-thermal emission is generally the jet or the jet termination regions, although there are some cases in which the radiation could also be generated outside the jet, like in the accretion disk corona (e.g. Lynden-Bell 1969; Pineault 1982; Torricelli-Ciamponi & Pietrini 2005), or the jet surroundings, like the stellar wind in high-mass MQs (e.g. Bosch-Ramon et al. 2008). The dominant non-thermal processes are synchrotron and inverse Compton (IC) emission for leptons (see, e.g., Blumenthal & Gould 1970), and proton-proton ($pp$) collisions (e.g. Kelner,

\footnote{Note the reader that the overview of high-energy processes presented here is not exhaustive.}
Aharonian, & Bugayov 2006), photo-meson production (e.g. Kehner & Aharonian 2008), and photodisintegration (e.g. Anchordoqui et al. 2007) for hadrons. Synchrotron radiation is produced by electrons that move in a magnetized medium and suffer Lorentz forces spiraling around the magnetic field lines. IC photons are produced when ambient photons are scattered by electrons getting a large increase of their energy and momentum. \(pp\) interactions, and photo-meson production resulting from proton-photon collisions, produce photons mainly via the production of neutral and charged pions that decay to gamma-rays, neutrinos, and charged muons/electron-positron pairs, which also emit photons. Finally, the disintegration of heavy nuclei by collisions with photons also lead to gamma-ray production. Further discussion of these processes in the context of MQs can be found in Bosch-Ramon & Khangulyan (2008). It is worth remarking that for environments with large matter densities, suitable for efficient gamma-ray production from \(pp\) interactions, relativistic Bremsstrahlung produced by electrons moving in the electric field of ions (e.g. Blumenthal & Gould 1970) could also be an efficient process, although generally it will be overcome by synchrotron and IC scattering.

As explained in Sect. 2.3., the jet base, the intermediate scale region, and the jet termination point, are the main regions where radiation is produced (basically along the whole jet), or expected to be produced when no direct spatial information is at hand, in sources harboring black holes and producing collimated outflows. The different processes that lead to non-thermal emission generate photons in wide bands of the electromagnetic spectrum. In the case of synchrotron, the emission spans from radio to X-rays and sometimes soft gamma-rays, depending on the electron energy and the magnetic field. In the case of IC, scattered photons can generally go from X-rays up to very high energies, although lower and higher energies are also possible. In hadronic processes, photons are produced in the gamma-ray range, and neutrinos and secondary pairs with similar energies to those of gamma-rays can also be generated. These secondary leptons will also radiate synchrotron and IC in wide energy ranges. For works regarding models of emission for different regions, mechanisms and spatial scales, in AGNs, GRBs and MQs, we refer to the literature (a non-exhaustive list of works and reviews: Jones et al. 1974; Ghisellini et al. 1985; Dermer et al. 1992; Sikora et al. 1994; Atoyan & Aharonian 1999; Aharonian 2002; Aharonian et al. 2006; Levinson 2006; Mészáros 2006; Böttcher 2007; Romero 2008b; Paredes 2008b; Bosch-Ramon & Khangulyan 2008; and references therein). Finally, the relativistic emitting particles themselves may escape the source and eventually reach the Earth, being detected as CRs. MQs in the low energy part but hardly at dominant levels (e.g. Heinz & Sunyaev 2002), and GRBs and AGNs at ultra high energies (e.g. Hillas 1984), are all expected contributors to the CR spectrum that reaches the Greisen-Zatsepin-Kuzmin (GZK) cut-off.

It is still worthy to note that in the innermost regions of jets, and in the surroundings of jets with nearby powerful photon sources, the absorption of gamma-rays by photon-photon interactions (e.g. Gould & Schröder 1967) will lead to the creation of secondary pairs that may, either via synchrotron or IC interactions, release again the absorbed energy. In case the magnetic field energy density were much smaller than the photon field energy density, efficient photon-photon
3. Discussion

3.1. Differences and similarities between source types

The different objects harboring a black hole and producing non-thermal radiation share the same basic elements: the black hole itself; an accretion disk; the presence of a jet or outflow; particle acceleration; and the candidates to dominant radiative processes discussed in previous section. Nevertheless, despite being so similar, there are still important differences between the black-hole powered sources beyond those obvious, i.e. the black-hole mass (and thereby size) and spin\(^2\), the distance to us, and the accretion rate. There are as well the environmental factors. For instance, the presence of a external source of photons, its location with respect to the jet, its luminosity and the energy of the photons, all can determine the spectrum at high and very high energies via IC, photo-meson production, photo-disintegration, or photon-photon absorption. The external medium density and velocity can be also very important regarding radiative processes like gamma-ray production from \(pp\) interactions, as well as for the jet propagation and stability. For instance, in the case of AGNs, different powers and medium densities give rise to different jet termination structures (e.g. Fanaroff & Riley 1974; for MQ jet-medium interactions, see e.g. Bordas et al. 2008 and references therein). Also, GRBs can show very different phenomena during their afterglow phase, when the jet terminates, depending on the characteristics of the environment, since it may be determined by a massive star wind for a collapsar long GRB, or could be a much less dense medium in the case of coalescence of two compact objects (Chevalier & Li 1999). In the case of MQs with a massive stellar companion, which fills the jet surroundings with powerful winds, hydrodynamical and non-thermal phenomena can take place given the presence of a magnetized and moving plasma colliding with the jet (e.g. Perucho & Bosch-Ramon 2008; Bosch-Ramon et al. 2008; Araudo, Bosch-Ramon & Romero 2009).

3.2. Prospects

Our present knowledge on the processes taking place in the black-hole vicinity, as well as in the outflows generated from there, is limited to the sensitivity, angular and energy resolution of the instruments working in the whole spectral range, mainly in radio, X-rays, and gamma-rays. Nevertheless, the prospects of the new instrumentation in all these ranges, with significant improvements in sensitivity and energy and angular resolution, are for the near future very important observational discoveries and thereby advances in our theoretical knowledge. For instance, VLBI interferometric techniques can unveil the closest regions to the black-hole horizon; polarization studies can say much about the role of magnetic

\(^2\)The charge is generally not considered in astrophysical black holes due to the short time in which they discharge by opposite charge accretion.
fields in the jet formation, collimation and evolution; radio and X-ray imaging can answer fundamental questions on the jet structure at different scales; and gamma-ray observations can unveil the physical processes taking place in plasmas of very extreme conditions, like in the jet base, in relativistic shell collisions, or in interactions with the environment.

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