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Letter to the Editor

Long-term remnant evolution of compact binary mergers

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ABSTRACT

We investigate the long-term evolution and observability of remnants originating from the merger of compact binary systems and discuss the differences to supernova remnants. Compact binary mergers expel much smaller amounts of mass at much higher velocities, as compared to supernovae and therefore the free expansion phase of the remnant will be short ($\sim$1−10 yr). But merger events with high mass ejection exploding in a low density environment remain in this ejecta dominated stage for several hundred years and in general the remnants will be observable for a considerable time ($\sim 10^6 - 10^7$ yr). Events releasing large amounts of kinetic energy may be responsible for a subsample of observed giant HI holes of unknown origin as compact binaries merge far away from star forming regions. If the ejecta consist primarily of actinides, on long timescales the expelled material will contain mainly the few quasi-stable nuclei in the actinides range. Consequently the abundance of each isotope in the ejecta might be of the order of a few percent. During their decay some actinides will produce observational signatures in form of gamma ray lines. We particularly investigate the gamma ray emission of Am 243, Cm 247, Cm 248 and Bi 208 and estimate their observability in nearby remnants. Detections of the gamma ray lines with INTEGRAL will be possible only in very advantageous cases but these remnants are promising targets for future instruments using focusing optics for soft gamma rays. Due to the low mass expelled in mergers and due to the lack of free electrons in the ejecta, the merger remnants might be significantly fainter in bremsstrahlung and synchrotron radiation than comparable supernova remnants. Hence merger remnants might represent a candidate for very recently discovered "dark accelerators" which are hard gamma ray sources with no apparent emission in other bands.

Key words. stars: neutron – binaries: close – ISM: bubbles – gamma rays: bursts – nucleosynthesis – abundances

1. Introduction

Observationally several neutron star binaries are identified to date (Stairs 2004) and it is expected that they inspiral as a result of gravitational waves and merge subsequently. These neutron star neutron star (NSNS) mergers were proposed as central engines of cosmological gamma-ray bursts (GRBs) already two decades ago (e.g. Paczyński 1986) and are nowadays considered as the most promising explanation for the subclass of short, hard GRBs discovered with BATSE (Kouveliotou et al. 1993). This scenario was very recently further supported by the first localization of a short GRB afterglow (Bloom et al. 2005; Gehrels et al. 2005). Theoretical progress on the physics of NSNS mergers was made by extensive numerical simulations (Ruffert et al. 1996, 1997; Lee et al. 1999; Rosswog & Davies 2002).

In this letter we focus on the impact of the ejecta of such merger events on the surrounding medium and on the observational consequences of remnants which are left behind these explosions. Simulations by above mentioned authors revealed that the mass ejected in NSNS mergers is typically small (about 10^{-4}–10^{-2} $M_\odot$), fast (a significant fraction of the speed of light) and furthermore that it possibly consists of heavy r-process nuclei. The mass of the ejecta might be increased by neutrino driven outflows of material from the quasi-stable super-massive neutron star (lifetime $\sim$100 ms) formed in the merger before it collapses to a black hole (Shibata et al. 2005). Additionally to the previously mentioned merger event of two NS we explore the development of remnants which contain a NS and a stellar mass black hole. Very recently simulations of mergers of neutron star black hole (NSBH) binaries with small mass ratios were performed by Rosswog (2005). These simulations showed that NSBH mergers are unlikely to drive GRBs but are likely to produce electromagnetic transients or even dark explosions, and that the mass expelled during the merger is generally much larger than in the NSNS merger case (about 0.01–0.2 $M_\odot$).

Remnants of GRBs with an hypernovae as central engines have been studied in the past with respect to their aspherical shape (Ayal & Piran 2001), their capability to produce giant HI holes in the interstellar medium (Efremov et al. 1998; Loeb & Perna 1998) and the lack of chemical signature left behind (Perna & Raymond 2000). HI holes might be promising candidates for GRB remnants as some of them seem to have no obvious origin (Rhode et al. 1999; Simpson et al. 2005; Hatzidimitrou et al. 2005). For the case of mergers a possible evolution szenario of the ejecta for the first few days after the event was discussed by Li & Paczyński (1998).

In contrast to previous work we explore in this letter the long-term evolution of remnants from compact binary mergers and investigate their appearance due to the signature of their chemical composition and due to various other emission mechanisms of the ejecta.

2. Evolution of the remnants

We investigate the evolution of remnants originating from the merger of compact binary systems and also discuss the difference to supernova remnants (SNRs). Compact binary mergers expel smaller amounts of mass at much higher velocities, as compared to supernova explosions. We use this fact and the long evolution time of the progenitors of mergers for the considerations in this section. Remnants of very energetic explosions within a surrounding medium evolve in several stages (e.g. Chevalier 1977):

2.1. Free expansion phase

The early expansion of the remnant will be driven mainly by the kinetic energy of the expelled material. This phase of free expansion will last until the swept up mass of the surrounding medium will equal the mass of the ejecta. Since the ejecta mass in compact binary mergers is small and the velocity of the material is very high in comparison to the mass and velocity of material expelled in supernova explosions, the remnant will reach the stage of equal mass very quickly. For a NSNS merger expelling only 10^{-3} $M_{\odot}$ in a medium of density 1 cm^{-3}, equality of mass will be reached within less then 5 years. However, in the case of a NSBH merger with a relatively high mass loss of 0.2 $M_{\odot}$ (still one order of magnitude lower than the mass ejected in a typical SN Ia) exploding in a low density environment of 10^{-6} cm^{-3} typical for the inter-galactic medium (IGM), the free expansion phase can last for about 1000 years. This scenario of NSBH mergers exploding into the IGM is likely as compact binaries might be expelled from galaxies by natal kicks during their formation. For constraints on the observability of this ejecta dominated phase see Sects. 3.2 and 3.3.

2.2. Sedov–Taylor phase

After the remnant has swept up an amount of mass from the ambient medium which is comparable to the mass ejected during the explosion, the interior of the bubble thermalizes and the expansion of the remnant is mainly pressure driven. This is described by the Sedov–Taylor solution. Due to the lower mass of material which is ejected in compact binary mergers, the time scale is shorter to reach the pressure driven phase for merger remnants than for a SNR. Hence remnants of mergers will start their pressure driven expansion with a much higher velocity than SNR. This is of particular interest in a hot medium with high sound velocity, as it has been shown that in hot media the pressure driven evolution of SNRs deviates from the Sedov–Taylor solution (Dorfi & Völk 1996; Tang & Wang 2005). In contrast to SNRs, the remnants of mergers will enter the pressure driven phase with a high expansion velocity and the explosion can still be described with the Sedov–Taylor solution. The evolution of the remnant will deviate from this approximation only after the expansion has decelerated to a velocity which is comparable to the sound velocity of the hot ambient medium. This evolution scenario of remnants is relevant for explosions which happen in elliptical galaxies containing hot gas or in case of the progenitor being part of the intracluster stellar population and exploding in the hot intra-cluster medium (ICM) (note that GRB 050509b possibly exploded in the ICM of a galaxy cluster, see Bloom et al. 2005 and Gehrels et al. 2005).

2.3. Late evolution of the remnant

The late phase evolution of a blast wave exploding into a cold uniform ambient medium will result in a cool thin expanding HI shell (Chevalier 1974, and for application on GRB remnants see Efremov et al. 1998 and Loeb & Perna 1998). The size and expansion velocity of the HI shells will be constrained by the amount of kinetic energy released in the explosion which for compact binary mergers is related to the mass of material ejected during the event. For NSNS mergers ejecting mass of 10^{-4} $M_{\odot}$ with a velocity of 0.5 c (with c being the speed of light), the kinetic energy released could be as small as $\sim 2 \times 10^{49}$ erg. This is nearly two orders of magnitude smaller than the average kinetic energy released in a supernova. On the other hand a NSBH merger ejecting 0.2 $M_{\odot}$ with a velocity of 0.5 c, the kinetic energy would be of the order of $\sim 5 \times 10^{52}$ erg, several times the kinetic energy produced in an average supernova explosion. Observationally identifying late stages of compact binary merger remnants will help constrain the energetics of such events. Events with high mass ejection may even produce giant expanding HI shells. We note that several large HI rings of unknown origin are indeed observed in a number of galaxies (Rhode et al. 1999; Simpson et al. 2005; Hatzidimitrou et al. 2005). Some of these observed HI holes do not show young star clusters at their centers which makes their emergence from multiple supernova explosions quite unlikely. NSBH mergers expelling a large amount of material might be the mechanism responsible for some of the observed HI shells as compact binaries take some time to merge during which they move away from star forming regions. HI rings might even help to identify the sites of NSBH merges which resulted in dark explosions (Rosswog 2005).

3. Observational signatures of the remnants

In this section we explore various emission mechanisms of the ejecta of compact binary mergers which consist of possibly very heavy elements, as compared to supernova ejecta. Considerations in this section are less well founded as the nature of the ejecta in compact binary mergers is not known very well. We also investigate the exciting possibility that these remnants might be related to the very recently discovered "dark accelerators".

3.1. Signature of r-process elements

The ejecta of compact binary mergers consists of exceptionally neutron rich material. This might result in the production and distribution of heavy r-process elements (Lattimer & Schramm 1974; Ruffert et al. 1997; Freiburghaus et al. 1999). The exact composition of the ejected material is not very well understood as many complicated physical processes play a role in neutron rich nucleosynthesis (e.g. Goriely et al. 2004). For low values of the relative electron number density of the ejecta, nucleosynthesis will lead to the production of mainly actinides in the expelled material (Ruffert et al. 1997). The early composition of the ejecta is difficult to determine but there might be certain constraints on the composition after a few thousand years. The actinides consist of only 18 nuclei with a half live time longer than 5000 years. Hence we expect that on timescales of a few thousand years the ejecta will be overabundant in the quasi stable nuclei as many of the decay chains of non stable nuclei will end at the quasi stable nuclei. So on long timescales if the ejecta consists of less then 20 isotopes we expect, as a first crude approximation, an abundance of the order of a few percent of every quasi stable specific nucleus in the expelled material. Future calculations with nuclear reaction networks will help to determine the values more precisely.

A long-term signature of the decay of radioactive nuclei might be observable in nearby remnants. A few of the radioactive actinides are sources of gamma radiation. Hence gamma ray lines could be used to identify the sites of past compact binary mergers. For example americium 243 with a half life time of 7370 years shows a strong gamma ray line at 74.66 keV (Akovali 1992) and curium 247 with a half life time of 1.56×10^7 years shows a strong gamma line at 402.4 keV (Schmorak 1992). For a given mass of the specific isotope (a few percent of the ejecta, see above) a correlated luminosity in the corresponding gamma ray line will result (see Fig. 1). Gamma ray lines with energies above 511 keV are of importance for observations as they lie above a possibly strong e^+e^- annihilation background and other isotopes could be useful: curium 248 will decay in spontaneous fission with the emission of gamma ray photon lines in the range of 94.9 to 605.91 keV with a half-life time of 3.48×10^5 years. An example for a non actinide r-process element with certain interest for this problem is bismuth 208 with gamma emission in the 2.61 MeV line and a half life time of 3.68×10^5 years (Martin 1986). The gamma ray satellite INTEGRAL is capable to observe 2×10^{32} erg of emission in the americium line only in the very advantageous case of a remnant being at a distance of 1 kpc, assuming an exposure of 10^6 s. But we note that most of the energy range of the gamma ray lines mentioned above is well suited to be observed with instruments using focusing optics for soft gamma rays by Laue lenses, which will achieve a by orders of magnitude better sensitivity (von Ballmoos & Smither 1994; Pisa et al. 2004; Frontera et al. 2005). The strength of the total galactic gamma ray emission of heavy r-process elements might help to estimate the merger rate of compact binaries in the galaxy. Once remnants of compact binary mergers are identified in this way, gamma ray lines might even be used to investigate the chemical composition of the ejected material.

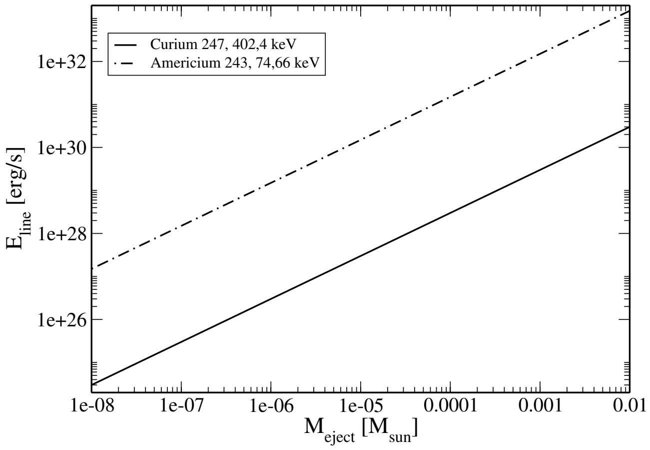

Fig. 1. Luminosity of two gamma ray lines as a function of the mass of the specific isotope.

3.2. Bremsstrahlung and X-ray line emission

The thermal bremsstrahlung emission of the remnant during the early evolution will be dominated by the ejecta. Since the mass of the ejecta in compact binary mergers is much smaller than in supernova explosions the density inside the remnants of these mergers will also be much smaller than the density in SNRs at a comparable state. Additionally the rarefraction of the interior of the exploding bubble will happen much faster in merger sites as they expand with very high velocities. Lower densities in the remnants will also have an impact on the emissivity of the material. For example the bremsstrahlung emissivity of the remnant scales with $\rho^2\epsilon^{1/2}$, with ρ being the density of the medium and ϵ being the specific internal energy (see Ayal & Piran 2001). Hence due to the lower densities, the bremsstrahlung luminosity of remnants of mergers might be significantly fainter than SNRs with a similar size. But several other processes will influence this result. The ejecta of mergers may consist of very heavy r-process nuclei (see also Sect. 3.1). High abundances of heavy nuclei can enhance the thermal bremsstrahlung (for a discussion on iron see Brighenti & Mathews 2005). Additionally very heavy elements are only fully ionized at very high temperatures. For example the binding energy of the K shell in uranium is about 115.6 keV (Bearden & Burr 1967) which means that uranium is fully ionized above a temperature of 1.3×10^9 K and line emission of Uranium is possible at lower temperatures. X-ray line emission of heavy elements may partly compensate the effect of decreased bremsstrahlung emission due to the low densities inside the remnants. The impact of these effects on the emissivity of the interior of the expanding bubbles has to be further analyzed in future.

3.3. Synchrotron emission

The synchrotron emission during the early evolution of the remnant will be mainly produced by the ejecta, which is exceptionally neutron rich and electron poor. As the expelled material consists of very heavy r-process elements (see Sect. 3.1), the high electron binding energy of very neutron rich and heavy nuclei will prevent the electrons to decouple from the ions (see Sect. 3.2). This will reduce the number of free electrons which are available for synchrotron radiation. The lack of free electrons in the expanding medium will lead to decreased synchrotron emission. It is further interesting to note that also the synchrotron volume emissivity is quite a strong function of the density. It scales with $\rho^2\epsilon^2$ of the emitting material for appropriate assumptions (for more details see Ayal & Piran 2001). Here again remnants of compact binary mergers will appear much fainter than supernova remnants due to their low interior densities.

3.4. Hard gamma ray emission

SNRs are known to be sources of hard gamma rays in the TeV range (see Aharonian et al. 2005a). Hard gamma rays are produced in the interaction of accelerated particles (for details see Aharonian et al. 2005a). We expect remnants of compact binary mergers also to radiate in hard gamma rays similarly to SNRs. Hence remnants of mergers may appear as sources of hard gamma rays, but due to the constraints of Sects. 3.2 and 3.3, with a significantly reduced bremsstrahlung and synchrotron radiation: So they might represent a candidate for recently discovered "dark accelerators" (Aharonian et al. 2005a,b) but this has to be further investigated as well. It is also important to mention that at least in the case of HESS J1303-631 the hard gamma ray emission seems to be connected to an association of young stars (see Aharonian et al. 2005b) which is difficult to explain with the proposed scenario.

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