Mergers of compact objects are considered prime sources of gravitational waves (GW) and will soon be targets of GW observatories such as the Advanced-LIGO, VIRGO etc. Finding electromagnetic counterparts of these GW sources will be important to understand their nature. We discuss possible electromagnetic signatures of the mergers. We show that the BH-BH mergers could have luminosities which exceed Eddington luminosity from unity to several orders of magnitude depending on the masses of the merging BHs. As a result these mergers could be explosive, release up to $10^{51}$ erg of energy and shine as radio transients. At any given time we expect about a few such transients in the sky at GHz frequencies which could be detected out to about 300 Mpc. It has also been argued that these radio transients would look alike radio supernovae with comparable detection rates. Multi-band follow up could, however, distinguish between the mergers and supernovae.

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1. Introduction

Compact binary mergers, such as neutron star-neutron star (NS-NS), neutron star-black hole (NS-BH) and black hole-black hole (BH-BH) are of great interest to gravitational wave (GW) astronomers because of the possibility of detecting GWs from nearby such events in the near future by using advanced sensitivity of GW observatories. While some of the ground based GW detectors are already operational
to designed sensitivities and some are being upgraded, several space based GW missions are in the initial stages of design studies. For example Laser Interferometric Gravitational wave Observatory (LIGO) and Virgo are being upgraded to second generation of GW detectors to be called advanced-LIGO and advanced-Virgo, respectively. Among the space based detectors Laser Interferometer Space Antenna (LISA) and DECI-Hertz Interferometer Gravitational wave Observatory (DECIGO) are at different levels of design studies. Space based detectors are mostly sensitive to GW events in the frequency band $10^{-4} – 0.1$ Hz and ground based detectors to those in the range $1 – 10^4$ Hz. At the even lower end of the frequency range will be Astrodynamical Space Test of Relativity using Optical Devices (ASTROD-GW)\textsuperscript{1} space based mission whose design is being studied and which will operate between $10^{-7} – 10^{-3}$ Hz.

GWs from the inspiralling compact binaries will probe Einstein’s General Relativity as well as alternative theories of gravity to an unprecedented accuracy in the strong field regime (see reviews by Arun K. G. and Kent Yagi in this issue). Detecting EM counter-part to GW signals is of immense importance for fundamental physics. Coincident EM-GW signals could potentially be used to build independent cosmological distance ladder,\textsuperscript{2,3} to probe the central engines of supernovae and gamma ray bursts (GRBs) as well as to study the evolution of massive stars and formation of compact objects such as BHs and NSs, to study galaxy-super massive black hole (SMBH) symbiosis and evolution\textsuperscript{4} and even to measure neutron star equation of state.\textsuperscript{5} Therefore it is also important to know what could be the electromagnetic signal produced by these mergers.

It has been proposed that the nucleosynthesis of heavy radio-active elements during the NS-NS merger could heat the ejecta and power a transient which will shine in optical/near-IR bands.\textsuperscript{6,7} This mechanism is similar to the one that powers optical brightness of supernovae. These transients would have luminosities somewhere between novae and supernovae with absolute visual magnitude $M_v \approx -15$ and would reach peak brightness on a timescale of $\approx 1$ day and could be detected out to $\approx Gpc$ distances.

Numerical simulations have made great progress in the last few years and have been providing deeper understanding of the issues involved in mergers and of the processes such as accretion and radiation during the short span of mergers. In short, these simulations predict that mergers of two compact objects, such as NS-NS & BH-BH mergers, could produce outflows with high velocities ($\beta \sim 0.1 – 0.8$), release energies up to $10^{49}$ erg\textsuperscript{8-11} and could power expansion of blast-waves in the surrounding medium. Such blast-waves would inevitably produce radio signals which could be detected from up to 300 Mpc or farther by the existing and upcoming radio telescopes.

Several astrophysical phenomena produce high velocity blast waves e.g. jets in AGNs and micro quasars, GRBs, supernovae etc. The shock waves generated during these explosions are the primary sources of associated radio transients in the universe. Their radio brightness is powered chiefly by synchrotron emission gener-
ated by the relativistic shock-heated electrons gyrating in the post-shock amplified magnetic fields. While majority of these events are discovered through the relatively short lived high-energy emission (optical, X-ray or \( \gamma \)-ray) associated with the explosion itself some events are likely to be discovered more efficiently by the radio emission. Radio observations of a recent type Ib/c supernova, SN2009bb, showed that it was expanding at mildly relativistic velocities (\( \beta \approx 0.8 \)) powered by the central engine.\(^{12}\) Such SN are usually associated with GRBs and are discovered by their intense but short \( \gamma \)-ray energy emission. Yet, SN2009bb had no detected \( \gamma \)-ray counter-part.

It is not clear if the mergers of compact objects will have associated prompt emission at high energies. However, we show here that a survey of radio sky at \( \approx \) GHz waveband would be ideal to discover radio transients produced by compact object mergers. With the advent of modern radio telescopes having deeper sensitivity and wide-field imaging capabilities it will be possible in near future to carry out such blind surveys to discover transients associated with the GW sources. Multi-wavelength observations will be useful in early identification of the nature of these sources.

## 2. Energy release during the merger of compact objects

A rotating black hole has a reservoir of free energy associated with its spin angular momentum which, in principle, could be extracted in various ways resulting in slowing down the rotation of the black hole. Ref.\(^{13}\) demonstrated this theoretically by carefully choosing particle trajectories; this particular energy extraction process is now known as the Penrose process. Subsequently, scattering of vacuum electromagnetic\(^{14}\) or gravitational\(^{15,16}\) or magnetohydrodynamic (MHD) waves\(^{17}\) were also shown to be possible means of tapping the energy. However, the Blandford-Znajek\(^{18}\) (BZ) mechanism of extracting the energy electromagnetically via Poynting flux appears to be the most likely workable mechanism in astrophysical settings. Numerical simulations have further shown the BZ mechanism not only to be viable but also a good candidate for powering variety of astrophysical sources such as the relativistic jets in active galactic nuclei, X-ray binaries and gamma ray bursts.\(^{19}\) A significant amount of energy could be released in the process with luminosity \( L \sim 3 \times 10^{43} B_4^2 M_8^2 \text{erg s}^{-1} \) where \( B \) is the magnetic field strength in Gauss through which the BHs of \( M \) solar mass moves. Throughout this paper we will follow the notation \( Q_a = Q/10^9 \).

Several authors have carried out numerical simulations of BH-NS & NS-NS mergers using either Newtonian or General Relativistic dynamics and to a varying degree of detailed treatment of microphysics. Despite these differences all simulations agree to the conclusion that significant amount of energy is released in fast moving ejecta during the mergers. For example, in the NS-NS mergers Ref.\(^{20}\) find \( 10^{51} \) erg of energy released to the ejecta moving with \( \beta = 0.2 \) where \( \beta \) is the ejecta velocity in units of speed of light. All NS-NS mergers lead to formation of accretion disk
which opens up possibilities for other sources of energy e.g. neutrino-antineutrino annihilation, BZ mechanisms etc. and possibly relativistic outflows. Overall, in the NS-NS merger, the amount of energy released could vary between $10^{49} - 10^{52}$ erg and outflow velocities from non-relativistic to relativistic.

On the other hand simulations of BH-NS mergers produce mildly relativistic but energetic ejecta with $\beta = 0.5$ and $10^{52}$ erg. BH-NS merger rates are quite uncertain and therefore their detectability is difficult to predict. But given their high energies and ejecta velocities they could comprise a non-negligible fraction of the overall gravitational and electromagnetic wave detections.

Recent simulations of SMBH mergers in the presence of imposed magnetic field suggested energy release in the form of Poynting flux outflow.\textsuperscript{11,21} Ref. 11 simulated merger of two $10^8 M_\odot$ BHs. The resulting Poynting flux flare had a luminosity of $L \approx 4 \times 10^{43}$ erg s$^{-1}$ and lasted for about 5 hr\textsuperscript{22} with total energy release of $\approx 2 \times 10^{48}$ erg in Poynting flux.

3. Radiation and dynamics of the outflows: Spectra and light curves

Consider an outflow with isotropic energy released in the explosion being $E$. In the case of supernovae typical observed energies are about $10^{46} - 10^{47}$ erg while those for compact mergers are expected to be about $10^{49}$ erg. The explosion drives a shock wave expanding into the surrounding medium which we consider to have a homogeneous density profile. The shock-wave sweeps the surrounding medium and heats it to relativistic temperatures. The shock converts bulk kinetic energy of the incoming material into thermal energy of the shocked material. The electrons in the shock-heated plasma are accelerated in the post-shock magnetic field to radiate synchrotron radiation. Below we derive the expected flux density evolution.

3.1. The Electron energy distribution

We adopt the conventional power law Lorentz factor distribution of shocked electrons with power-law index $p$:

$$n_e(\gamma_e) d\gamma_e = K_e \gamma_e^{-p} d\gamma_e$$

for $\gamma_m \ll \gamma_e \ll \gamma_u$, where $\gamma_m$ and $\gamma_u$ are the lower and upper energy cut-offs of the distribution and $\gamma_e$ the electron Lorentz factors.

At this point it is important to note that not all the shocked electrons will end up in the non-thermal energy distribution. This fraction depends on the speed of the shock-wave. When the shock-wave is ultra-relativistic most of the shocked electrons can end up building the non-thermal distribution, which may be the case for GRBs. It may not be true, however, for non-relativistic blast waves such as in the present case and in the supernovae. While a detailed treatment of the dependence of $\epsilon_r$ on the shock speed is beyond this article, for simplicity we assume that fraction to be a constant. The value of $\gamma_m$ and $K_e$ can then be found be assuming that a constant
fraction $\epsilon_r$ of all the shocked electrons end up in the non-thermal electron energy distribution and that the amount of energy available for the electron acceleration is a constant fraction ($\epsilon_e$) of the total thermal energy density $U'_{th}$.

\[ \int_{\gamma_m}^{\gamma_u} n_e(\gamma_e) \, d\gamma_e = 4\epsilon_r n \]  
\[ \int_{\gamma_m}^{\gamma_u} \gamma_e m_e c^2 n_e(\gamma_e) \, d\gamma_e = \epsilon_e U'_{th} \]  

The primed quantities are measured in their local rest frame i.e. in the frame of the shocked material. Shock wave efficiently converts its kinetic energy into internal energy of the shocked material. For a shock wave moving several times faster than the local sound speed density compression of factor 4 is achieved and the compressed medium trails the shock wave with speed lower by that factor. Further, it can be shown that the thermal energy density of the shocked medium is given by

\[ U'_{th} = \frac{9}{8} n m_p \beta^2 c^2. \]  

Using Eqn. 1, 2, 3 and assuming $\gamma_u \gg \gamma_m$ one obtains

\[ \gamma_m = \epsilon_e \frac{9}{32} \frac{m_p}{m_e} \frac{p-2}{p-1} \beta^2 \]  
\[ K_e = 4\epsilon_r n (p-1) \gamma_m^{-1} \]  

3.2. Post-shock magnetic field

It is assumed that similar to $\epsilon_e$ a fraction $\epsilon_B$ of the post-shock thermal energy goes into the magnetic field.

\[ \frac{B'^2}{8\pi} = \epsilon_B U'_{th} \]  

Similar to $\epsilon_e$, in our entire discussion we will treat $\epsilon_B$ as a constant in time.

3.3. Synchrotron Spectrum

It is assumed that the shocked electrons gyrate in the post-shock magnetic fields and radiate synchrotron radiation. Ref. 23 generalised the standard synchrotron function of Ref. 24 by integrating over isotropic distribution of pitch angles and then estimated the dimensionless frequency $x_p$ at which the dimensionless flux peaks $F(x_p) = \phi_p$. These values, they show, are considerably different than the usually used standard values. Therefore, we will continue to follow the treatment and notation of Ref. 23. For a power law distribution of radiating electrons, the values of $x_p$ and $\phi_p$ depend on the distribution index $p$ as shown in Ref. 23, where for our fiducial $p = 2.5$ we get $x_p = 0.5$ and $\phi_p = 0.65$. We adopt the shape of the synchrotron spectrum as given by Ref. 25.

3.3.1. $\gamma_m$ and corresponding spectral break in the Synchrotron Spectrum

The power-law distribution of the electrons has a lower Lorentz factor cut-off which we identify as $\gamma_m$ (Equation 4). We adopt expression by Ref. 23 for the characteristic
synchrotron frequency corresponding to $\gamma_m$, 
\[
\nu'_m = \frac{3x_p \gamma_m^2 qB'}{4\pi m_e c},
\] (7)
where $q$ is the electric charge, $m_e$ is the mass of electron and $x_p$ is the dimensionless frequency discussed in.\textsuperscript{23} The value of $x_p$ depends on the electron energy distribution index $p$. The spectrum will fall for $\nu' > \nu'_m$.

### 3.3.2. Spectral break due to synchrotron self absorption

By approximating the thickness of the shocked radiating plasma to be $dr = r/12$ the optical depth can be approximated as $\tau_\nu \sim \alpha_\nu \, dr$. For the synchrotron self-absorption coefficient we used equation 6.53 of Ref.\textsuperscript{24} and inverted the relation $\tau_\nu = 1.0$ to obtain $\nu'_a$.

### 3.3.3. Peak flux of the Synchrotron Spectrum

Assuming that a fraction $\epsilon_r$ of all the shocked electrons, $N_e$, contribute to the non-thermal synchrotron radiation, the instantaneous peak flux at $\nu_m$ can be estimated as
\[
F_m = F_\nu(\nu_m) = \frac{\epsilon_r N_e P'_\nu_m}{4\pi d_L^2},
\] (8)
where $N_e = (4\pi/3)R^3n(1 + X)/2$ and $P'_\nu_m$ is the synchrotron power per electron averaged over an isotropic distribution of pitch angles\textsuperscript{23}
\[
P'_\nu_m = \phi_p \frac{\sqrt{3}q^3B'}{m_e c^2}.
\] (9)
We also have the luminosity distance $d_L$ and the hydrogen fraction $X$.

### 3.4. Evolution of the Spectrum

The density profile of the surrounding medium which the shock-wave is ploughing through plays an important role in dictating the dynamics of its evolution and subsequently that of the radiation spectrum. There is a strong evidence that massive stars are the progenitors of radio SNe of Type Ib/c. This means that the SN generated shock-wave should be expanding into the stellar wind of the progenitor star. Compact objects which are products of SNe such as NSs receive significant kick velocity at the birth and are thrown out of the location where they were born. Therefore, it is expected that the merger of compact objects would take place in the homogeneous inter-stellar medium or in the distant galactic halos. Considering this we calculate the spectral and temporal evolution in homogeneous ISM below in section 3.4.1. For completeness we calculate the evolution in wind density profile also in section 3.4.2.
3.4.1. Homogeneous inter-star-ler medium

The instantaneous synchrotron spectrum can then be characterized by two break
frequencies \( \nu'_m \) and \( \nu''_m \) and the peak flux \( F'_m \). Because the shock wave, and therefore
the radiating plasma behind it, is expected to be moving at non-relativistic or
mildly relativistic velocities we have neglected relativistic effects including doppler
boosting, for simplicity. As a result of this we use \( \nu'_m = \nu_m, \nu''_m = \nu_a \) and \( F'_m = F_m \)
where unprimed quantities are measured at an observer on the Earth. For the
temporal evolution, initially the ejecta will coast along with a constant
velocity \( \beta (\neq \beta_{dec}) \) and therefore \( R = \beta_{dec}ct \). Equations 4-9 then give

\[
F_m(t_{\oplus,d}) \approx 0.15(\gamma_{dec}\beta_{dec})^4 n^{3/2} \epsilon_{\phi}^3 (X + 1)(z + 1) \sqrt{\epsilon_B \epsilon_e d_{L,100}^{-2}} \mu \text{Jy}
\]

\[
\nu_m(t_{\oplus,d}) \approx 10^{12}(\gamma_{dec}\beta_{dec})^5 \sqrt{m(p - 2)^2} x_p \sqrt{\epsilon_B \epsilon_e^2 (p - 1)^{-2} (X + 1)^{-2}} \text{Hz}
\]

along with the synchrotron self absorption frequency

\[
\nu_a(t_{\oplus,d}) = 10^n n^{4/5}(p-1)^{8/5} \epsilon_{\phi}^{3/5} (X + 1) \epsilon_{\epsilon}^{1/5} (\gamma_{dec}\beta_{dec})^{-1} (p-2)^{-1} \left( \frac{p + 2}{p + 2} \right)^{-3/5} \epsilon_e^{-1} \epsilon_{\epsilon}^{3/5}.
\]

when \( \nu_a \ll \nu_m \) and

\[
\nu_a(t_{\oplus,d}) = 10^{12} n \epsilon_{\phi}^{p+6} \epsilon_{\epsilon}^{p+2} (1+X) \epsilon_{\epsilon}^{5/2} \epsilon_B (\gamma_{dec}\beta_{dec})^5 \Gamma(\frac{3p + 2}{12}) \Gamma(\frac{3p + 22}{12})
\]

when \( \nu_a \gg \nu_m \). We take \( t_{\oplus,d} \) to be the time since the explosion as measured by the
observer in days and \( d_{L,100} \) to be the luminosity distance in units of 100 Mpc.

After the ejecta has swept up enough matter, comparable to its kinetic energy,
it will start to decelerate. This will happen at a distance

\[
R_{dec} \approx 10^{17} E_{49}^{1/3} n^{-1/3} \beta_{dec}^{-2/3} \text{cm}
\]

and at time

\[
t_{dec} \approx 45 E_{49}^{1/3} n^{-1/3} \beta_{dec}^{-5/3} \text{days}
\]

After this epoch shocked plasma would assume Sedov-von Neumann-Taylor (SNT)
self similarity and the ejecta will decelerate with \( \beta = \beta_{dec} (R/R_{dec})^{-3/2} \) while its
temporal evolution is given by \( R = R_{dec} (t/t_{dec})^{2/5} \). Therefore the evolution of the
spectrum for \( t > t_{dec} \) is given by:

\[
F_m(t) = F_m(t_{dec}) \left( \frac{t}{t_{dec}} \right)^{3/5}
\]

\[
\nu_m(t) = \nu_m(t_{dec}) \left( \frac{t}{t_{dec}} \right)^{-3}
\]

\[
\nu_a(t) = \nu_a(t_{dec}) \left( \frac{t}{t_{dec}} \right)^{6/5}
\]
3.4.2. Wind inter-stellar medium

During their lifetime massive stars drive strong winds and loose mass. In the process density profile of the immediate environment around these stars gets modified. For a constant rate of mass loss $\dot{M}$, and constant wind velocity $V_w$ the interstellar medium density around the star assumes a power law profile $\rho = A \rho_{\text{wind}}$ up to the wind termination shock. By assuming $\dot{M} = 10^{-5} \text{M}_\odot \text{yr}^{-1}$ and $V_w = 1000 \text{ km s}^{-1}$, $A$ can also be written down as $A = \dot{M}/(4 \pi V_w) = 5 \times 10^{11} \text{A}_* \text{ g cm}^{-1}$. Using the wind density profile along with Equations 4-9 and the fact that initially the ejecta will be coasting along at a constant velocity $\beta (= \beta_{\text{dec}})$ and therefore $R = \beta_{\text{dec}} c t$ gives

$$F_m(t_{\odot,d}) \approx 1.4 \times 10^6 A_*^{3/2} (1 + X)(1 + z)(\gamma_{\text{dec}} \beta_{\text{dec}})^4 \sqrt{\epsilon_B} \phi_p d_{L,100}^{-2} \mu \text{Jy}$$ (19)

$$\nu_m(t_{\odot,d}) \approx 2 \times 10^{14} \sqrt{A_*} (\frac{p - 2}{p - 1})^2 x_p (\gamma_{\text{dec}} \beta_{\text{dec}})^4 \sqrt{\epsilon_B} \epsilon_t^{1/2} d_{L,100}^{-1} (1 + X)^{-2} \text{ Hz}$$ (20)

$$\nu_a(t_{\odot,d}) \approx 8 \times 10^{10} A_*^{4/5} [\frac{(p - 1)^{8/5}(p + 2)^{3/5}}{(p - 2)(3p + 2)^{3/5}}] (1 + X)^{1/5} \epsilon_t^{1/4} d_{L,100}^{-1} (\gamma_{\text{dec}} \beta_{\text{dec}})^{-13/5} \epsilon_e^{-1} \epsilon_r^{3/5} \text{ Hz}$$

This evolution will continue until the shock-wave sweeps material comparable to its kinetic energy after which the ejecta will decelerate. This will happen at a distance of $R = R_{\text{dec}}$ given by

$$R_{\text{dec}} \approx 5.3 \times 10^{15} E_{49} A_*^{-1} \beta_{\text{dec}}^{-2} \text{ cm}$$ (22)

and at time $t_{\text{dec}} = R_{\text{dec}}/\beta_{\text{dec}} c$:

$$t_{\text{dec}} \approx 2 E_{49} A_*^{-1} \beta_{\text{dec}}^{-3} \text{ days}$$ (23)

After this epoch the shock wave expands as $R = R_{\text{dec}} (t/t_{\text{dec}})^{2/3}$ and the ejecta decelerates as $\beta = \beta_{\text{dec}} (R/R_{\text{dec}})^{-1/2}$. The evolution of the spectrum for $t > t_{\text{dec}}$ is given by:

$$F_m(t) = F_m(t_{\text{dec}}) \left( \frac{t}{t_{\text{dec}}} \right)^{-1/3}$$ (24)

$$\nu_m(t) = \nu_m(t_{\text{dec}}) \left( \frac{t}{t_{\text{dec}}} \right)^{-7/3}$$ (25)

$$\nu_a(t) = \nu_a(t_{\text{dec}}) \left( \frac{t}{t_{\text{dec}}} \right)^{-2/5}$$ (26)

The evolution of all the spectral parameters thus obtained is summarized and compared with that in the homogeneous density profile in Table 1.

The overall lightcurve could be calculated using the spectral shape and the evolution of spectral breaks in Table 1. For the simplest case of optically thin spectrum, i.e. $\nu_a \ll \nu_m \ll \nu$, the light curve after merging the pre- and post-deceleration regimes, is given by:

$$F_\nu(t) = F_\nu(t_{\text{dec}}) \left[ \left( \frac{t}{t_{\text{dec}}} \right)^{-\alpha_1 s} + \left( \frac{t}{t_{\text{dec}}} \right)^{-\alpha_2 s} \right]^{-1/s},$$ (27)
Simulations of two merging black-holes showed emergence of Poynting
\[ F_{\nu}(t_{\text{dec}}) = \frac{F_m}{\nu_m} \]
where \( a_1 = 3.0 \) and \( a_2 = 3/5 + 3b = -0.3(5p - 7) \approx -5/3 \) for \( p = 2.5 \), and we use a value \( s = 2 \) to smoothly join the two regimes. The peak of the light curve which occurs at \( t = t_{\text{dec}} \) is given by:
\[ F_{\nu} \propto \frac{t^3}{t_{\text{dec}}^3} \quad \text{for} \quad t < t_{\text{dec}} \]
and
\[ F_{\nu} \propto t^{-5/3} \quad \text{after deceleration has begun.} \]

4. Expected Event Rates of NS-NS mergers

It can be shown that for the reasonable values of parameters the spectrum should be optically thin at radio wavelengths with:
\[ F_{\nu} \propto \nu^{-(p-1)/2} \]
by the time they reach their peak brightness around \( t = t_{\text{dec}} \). Their peak brightness at a specific observing frequency could therefore be given as:
\[
F_{\nu,\text{peak}} \approx 23f_p E_{49} n^{(p+1)/4} \beta_{\text{dec}}^{5(p-7)/2} \epsilon_B e^{5/4} \epsilon^{p-1} d_{L,100}^{-2} mJy^{-1/2} \quad \text{mJy}
\]
\[
\approx 128E_{49}^{7/4} \beta_{\text{dec}}^{11/4} \epsilon_B^{3/2} \epsilon^{p-1} d_{L,100}^{-2} \quad \text{mJy}^{-3/4}
\]
where \( f_p = \phi_p \left( \frac{2x_{10^{-2}}}{2.3x_{10^{-3}}} \right)^{(p-1)/2} \left( \frac{p-2}{p} \right)^{p-1} \). A radio telescope with a sensitivity of about 50 \( \mu \text{Jy at} \approx \text{MHz frequencies can detect such transients out to about 300 Mpc.} \]

If \( R \) is an intrinsic event rate then an all sky-snapshot should be able to detect:
\[ N_{\text{all-sky}} = R \nu \Delta t \]
which occur within the volume \( V \) limited by the telescope sensitivity and remain detectable at \( \Delta t \) amount of time. Following Ref. 9, 10 we set \( \Delta t \approx t_{\text{dec}} \) and use \( R_{\text{CM}} = 300 R_{300} \text{ Gpc}^{-3} \text{yr}^{-1} \) for NS-NS merger rate giving:
\[
N_{\text{all-sky}} \approx 1E_{49}^{11/6} n^{47/48} \beta_{\text{dec}}^{59/24} \epsilon_{B,0.1}^{21/16} \epsilon_{e,0.1}^{9/4} \epsilon_e^{3/2} \epsilon_r^{3/2} R_{300} \left( \frac{F_{\nu,\text{lim}}}{50 \mu \text{Jy}} \right)^{-3/2} \quad \text{mJy}^{-9/8} \quad \text{Hz}
\]

It is clear from above equation that the detection rate is strongly dependent on two parameters: the energy released in the blast-wave and its velocity. For the reasons of simplicity we have used the approximation \( \Delta t \approx t_{\text{dec}} \) where \( \Delta t \) is the duration for which the event remains above the telescope sensitivity and therefore is visible. In practice, \( \Delta t > t_{\text{dec}} \) by a factor of few and therefore actual rate of detection could be higher by that factor.

5. BH-BH binary mergers

It has been shown that black hole’s huge reservoir of energy, in the form of its rotational energy, could be tapped at least theoretically via the Blandford-Znajek mechanism. Some of the brightest and energetic objects in the universe have been thought to be powered by this mechanism which plays central role in the models explaining Gamma Ray Bursts, Active Galactic Nuclei etc. Progress in numerical simulations over the years, however, have prompted the BZ mechanism from being merely speculative or theoretical to being close to the working model in nature. Simulations of two merging black-holes showed emergence of Poynting
flux jets with luminosities and energy scales as predicted by the BZ mechanisms.\textsuperscript{11,22} The energy output in the presence of surrounding plasma was an order of magnitude larger than in the electrovacuum case, demonstrating that the plasma facilitates efficient tapping of the black-hole energy.

Ref. 11 carried out a simulation of the interaction of a binary BH system, consisting of two non-spinning BHs of equal masses (\(M = 10^8 M_\odot\)), with the surrounding magnetic field and conducting plasma. As the GW emission drained off energy and momentum the BHs collided and merged, settling into a larger rotating Kerr BH with spin \(a = Jc/GM^2 \approx 0.67\) where \(J\) is the BH’s angular momentum. The merging BHs gave rise to a flare of Poynting flux (\(L \approx 10^{43}\) erg/s lasting over 5 hrs) coincident with the peak of GW emission.

The electromagnetic energy released in the form of Poynting flux during the BH-BH merger could be expressed as a sum of spin and speed components:\textsuperscript{22}

\[
L_{\text{total}} = L_{\text{spin}} + L_{\text{speed}}
\]

\[
= 0.87 \left(\frac{a}{0.6}\right)^2 + 127\beta^2 \right) M_8^2 B_4^2 L_{43} \text{ erg s}^{-1}
\]

As can be seen, the non-spinning contribution to the total luminosity exceeds that due to spin for \(\beta \gtrsim 0.1\) while \(\beta \gg 0.1\) in the last stages of merger and as a result the luminosity rises sharply. Some of this may emerge as a synchrotron emission, as suggested by Ref. 11 in the form of a flare and the rest could be dissipated at large distances and could power the adiabatic expansion of the shock front traveling at relativistic to mildly relativistic speeds as the total luminosity could easily exceed Eddington luminosity of the system. The luminosity could be expressed in the units of Eddington luminosity \(L_{\text{Edd}}\) i.e.

\[
\frac{L_{\text{total}}}{L_{\text{Edd}}} \approx 0.1 \times B_4^2 M_8
\]

where we have used \(\beta = 0.8\). Conservatively, Ref. 11 chose the magnetic field such that \(L \sim 0.002 L_{\text{Edd}}\) at merger. The limiting magnetic field required to reach this limit is \(B = 6 \times 10^4 \sqrt{M_8} G\). The inner accretion disk could develop significantly high magnetic field, however, as shown by Ref. 27, 28. For \(B_4 = 10\) one gets \(L_{\text{total}} \approx 7 \times L_{\text{Edd}}\) for the merger of BHs with \(M = 10^8 M_\odot\). As shown by Ref. 27, 28 and Ref. 29 magnetorotational instability at the inner edge of the accretion disk could amplify magnetic fields to even larger values dependent on the mass of the central object \(B \approx 10^6 M_8^{-7/20} G\). With this magnetic field the whole range of BHs masses, from stellar to supermassive, result in super-Eddington luminosities having \(L_{\text{total}}/L_{\text{Edd}}\) ranging from unity to several hundreds.

From their simulations Ref.11 estimate the total electromagnetic energy radiated during the merger to be \(E \approx 2 \times 10^{48}\) erg. As the BH-BH spiral in and come closer, their speed increases sharply and so does the radiated luminosity. The total energy
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could then be estimated by integrating over the merger duration:

\[ E \approx 127 \int_{t(\beta_1)}^{t(\beta_{\text{max}})} \beta^2 M_8^2 B_1^2 L_{43} dt \]  

(33)

where the integration starts from moderate velocity \( \beta_1 \) to the terminal velocity \( \beta_{\text{max}} \). Following Ref. 30 the evolution of circular velocity is given by \( d\beta/dt = A\beta^9 \) where \( A \) is the proportionality constant \( A = (96/15)c^3\eta/GM \) and \( \eta = m_1m_2/M \) is the mass ratio of merging black-holes of masses \( m_1 \) & \( m_2 \) with the total mass being \( M = m_1 + m_2 \).

Knowledge of actual magnetic fields in the circum-binary disks threading the BHs appears to be a limiting factor in further understanding of these mergers. Therefore instead of assuming optimistically high energy release, we will follow Ref. 11 and Ref. 29 such that \( L \approx \epsilon_{\text{Edd}} L_{\text{Edd}} \) and absorb our ignorance about the magnetic fields and details of emission mechanism in the parameter \( \epsilon_{\text{Edd}} \). The total energy release could then be expressed as

\[ E \approx 2 \times 10^{50} \epsilon_{\text{Edd}} \eta^{-1} M_8^2 \]  

(34)

where we have assumed moderate values for \( \beta_1 = 0.3 \) and \( \beta_{\text{max}} = 0.4 \).

Thus, the most massive BH-BH mergers could be comparable to or more energetic than the NS-NS mergers. Other characteristics, such as the rise time and brightness which are important parameters for carrying out searches of the associated electromagnetic transients will also depend on the merger masses and energy outputs.

Ref. 29 has shown that such a flare of synchrotron radiation could be seen from cosmological distances (\( z \sim 2 \)). Since \( \tau_{\text{flare}} \propto M_{\text{BH}} \) stellar mass BHs would produce flares which will be both shorter and less intense than those produced by SMBHs. Therefore recovering most of the stellar mass mergers would require a survey of rapid cadence. As shown by Ref. 29 a radio survey operated around GHz frequencies with a cadence of 10s would be able to see \( \approx 24 \) mergers per year most of which would be due to stellar mass mergers. A slow cadence will not see stellar mass mergers but will see about 3 mergers per year produced by SMBHs.

It is possible that a comparable amount of energy is released in the expansion of the shock wave into the surrounding material. This shock wave can shine as the “afterglow” transient in the days after the flare peaked during the merger and GW emission. The amount of energy will depend on the masses of the merging black holes as per the Equation 34 above and can therefore range from \( 10^{36} \) erg for \( M = 10 M_\odot \) to \( 10^{51} \) erg for \( 10^8 M_\odot \) BHs.

The merging masses will also determine the timescales over which the transient will be shining. As can be seen from Eqn. 16 the shock will start to decelerate at \( t_{\text{dec}} \approx 45E_{19}^{1/3} \) days around which the EM transient will be at its peak brightness; effectively between a few minutes for the mergers of stellar mass BHs to a few months for \( M = 10^8 M_\odot \), respectively.
Peak brightness of the transient at a distance of 100 Mpc would be \( F_{\nu,\text{peak}} \approx 0.5 E_{49} \) mJy implying that mergers of stellar mass BHs might be too faint to detect but those of super-massive BHs could be detectable out to about Gpc with the present sensitivity of the radio telescopes.

6. Identifying radio “afterglow” of compact mergers

As discussed above the expected detection rate of mergers of compact objects events and SNe will be comparable (a few events per year). Evolution of their light curves would be similar and therefore distinguishing them from each other would be important. Multi-wavelength observations, especially optical spectroscopy will be useful to identify compact mergers from other similar transients.

The most important early distinction could be made by using optical observations. The compact merger events are expected to be faint in the optical unless their optical light is powered by a process other than synchrotron radiation, such as the decay of radioactive elements synthesized in the explosion. Deep limits on the optical brightness of a transient should be able to rule out the presence of SNe. Furthermore, optical spectra of SNe have been studied in detail and its evolution in time is also very well understood (e.g. for a review see Ref. 31. Also see Ref. 32 and references therein.) Optical light curves of SN also have characteristic shapes.33 Together these features should be able to identify a SN from a compact merger event as early as within a week to a month from the discovery. Over longer time-scales multi-wavelength radio observations of such transients can play crucial role in making the distinctions by carrying out detailed calorimetry of explosions. Multi-band colorimetry has been carried out in several GRB afterglows and SNe.34-37 Compact mergers are expected to release up to \( 10^{49} \) erg as kinetic energy as opposed to SNe whose typical energy budgets are \( 10^{50} - 10^{51} \) erg.

7. Conclusion

In the near future several advanced gravitational wave observatories will become operational and are expected to detect first GWs. This will open an entirely new window on the transients and on the Universe. GWs will become a new probe of the Universe and our understanding of almost every aspect of the Universe, from stellar evolution, galaxy formation to the early universe, will be revolutionized. To substantially exploit the benefits of GW discoveries, however, it will be important to discover EM counterparts of GW sources.

Among other sources of gravitational waves, mergers of compact objects such as NS-NS, NS-BH and BH-BH are considered prime sources of GWs. Many of these mergers could be explosive and would drive blast waves, relativistic or non-relativistic, into the surrounding medium and shine as bright radio transients. We have shown that these events would produce transients bright enough to be detected from up to 300 Mpc and about half a dozen should be visible in the entire sky at any given time to the radio telescopes operating at GHz frequencies.
The arrival of GW detectors online is most opportune as several modern technology radio telescopes will soon be operational across the globe: already operational Merchison Widefield Array\textsuperscript{a} and Australian SKA Pathfinder\textsuperscript{b} (to be operational by 2013) in Australia, MeerKat\textsuperscript{c} (by 2018) in South Africa, Low Frequency Array \textsuperscript{d} in the Netherlands and Europe is already operational while Apertif \textsuperscript{e} in the Netherlands will be operational by the end of 2012, and the Square Kilometer Array \textsuperscript{f} (by 2024) from South Africa and Australia. Besides having significantly better sensitivity they also have wide field imaging capabilities which makes continuous scanning of the sky possible. Wide and moderately deep sky surveys carried out by these telescopes should uncover at least a few transients each year. With comparatively better localization of the transients made available by these telescopes spatial coincidence of the transients should reveal their association with the GW sources detected by GW observatories.

The GHz frequency radio sky survey appears to be a promising method to discover transients associated with the outflows generated by mergers of compact objects. Blind radio surveys should be able to detect about a few of such sources at any given time in the sky. Mergers of NS-NS binaries should produce transients with total energy output of about $10^{49}$ erg. The total energy output of BH-BH binary mergers is less uncertain but is likely to be lower by several orders of magnitude for stellar mass BH mergers compared to those of the super-massive BHs. As a result afterglow like emission in the stellar mass BH mergers would be very faint to be detectable for the current or near future radio telescopes.

The detection rate of compact object mergers will be comparable to that of the radio supernovae. Besides, the light curve evolution of radio supernovae and afterglows from compact object mergers would look alike. Therefore distinguishing the two classes from each other observationally will be important. This could be done easily at early times by optical spectroscopy. Detailed calorimetry could be carried out by long term multi-band follow up which could also aid in distinguishing the compact object mergers from radio supernovae.

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\textsuperscript{a}http://www.mwatelescope.org/
\textsuperscript{b}http://www.atnf.csiro.au/projects/mira/
\textsuperscript{c}http://www.ska.ac.za/meerkat/index.php
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Table 1. **Time Dependence of Spectral Parameters**: We give the temporal power-law index (i.e., $a$ in $x(t) \propto t^a$ for parameter $x$) of the peak flux density $F_m$, the peak frequency $\nu_m$, and the self-absorption frequency $\nu_a$ (considered in two limits compared to $\nu_m$). Here, $p$ is the power-law index for the electron energy distribution: $n_e(\gamma_e) \propto \gamma_e^{-p}$.

| Parameter | Homogeneous density profile | Wind density profile |
|-----------|----------------------------|---------------------|
|           | $t \ll t_{dec}$ | $t \gg t_{dec}$ | $t \ll t_{dec}$ | $t \gg t_{dec}$ |
| $F_m$     | 3                      | 3/5                 | 0                   | -1/3               |
| $\nu_m$   | 0                      | -3                  | -1                  | -7/3               |
| $\nu_a(\ll \nu_m)$ | 3/5               | 6/5                 | -1                  | -2/15              |
| $\nu_a(\gg \nu_m)$ | 2/(p + 4) | -(3p - 2)/(p + 4) | -1                  | -(7p - 6)/(3p + 4) |