ULTRAHIGH-ENERGY COSMIC RAYS AND BLACK HOLE MERGERS

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ABSTRACT

The recent detection of the gravitational-wave source GW150914 by the LIGO collaboration motivates a speculative source for the origin of ultrahigh-energy cosmic rays as a possible byproduct of the immense energies achieved in black hole (BH) mergers, provided that the BHs have spun, as seems inevitable, and there are relic magnetic fields and disk debris remaining from the formation of the BHs or from their accretion history. We argue that given the modest efficiency <0.01 required per event per unit of gravitational-wave energy release, merging BHs potentially provide an environment for accelerating cosmic rays to ultrahigh energies. The presence of tidally disrupted planetary or asteroidal debris could lead to associated fast radio bursts.

Key words: astroparticle physics – gravitational waves – stars: black holes

1. INTRODUCTION

The extragalactic origin of ultrahigh-energy cosmic rays (UHECRs) remains a mystery, whereas galactic cosmic rays are generally interpreted as being Fermi accelerated via shocks around supernova remnants. We point out here that the recent detection of the gravitational-wave source GW150914 at a redshift \(z \sim 0.09 \pm 0.03\) (luminosity distance \(D_{\text{gw}} = 410 \pm 180\) Mpc) by the Laser Interferometer Gravitational Wave Observatory (LIGO; Abbott et al. 2016a) provides new light on a speculative source for the origin of ultrahigh-energy cosmic rays. The inferred event is the merger of a black hole (BH) binary whose members have masses of \(M_1 = 36^{+5}_{-4} M_{\odot}\) and \(M_2 = 29^{+4}_{-3} M_{\odot}\), with a final BH mass \(M = 62^{+4}_{-4} M_{\odot}\), and \(E_{\text{gw}} = 3.0^{+0.5}_{-0.5} M_{\odot} c^2 \sim 5.4 \times 10^{53}\) erg radiated in gravitational waves, and a peak gravitational-wave luminosity of \(L_{\text{gw,peak}} = 3.6^{+0.5}_{-0.4} \times 10^{56}\) erg s\(^{-1}\). The inferred population rate is \(\rho_{\text{BH}} \sim 2 - 400\) Gpc\(^{-3}\) yr\(^{-1}\) (Abbott et al. 2016b).

Could there be an electromagnetic counterpart? We speculate that the most likely counterparts are at extremely high energy where the injection requirements are modest in terms of mass. Here, we focus on ultrahigh-energy cosmic rays as a possible byproduct of the immense energies achieved in BH mergers, especially if the BHs have spin, as seems inevitable, and there are any relic magnetic fields and debris remaining from the formation of the BHs. The most likely long-lived debris would be a system of planets or asteroids that would be dynamically re-energized to produce an occasional plunging orbit in the course of the merger, with tidal debris feeding an accretion disk. We note that the LIGO limit on the final spin amplitude of the remnant BH is \(0.67^{+0.05}_{-0.07}\). Ultrahigh-energy neutrinos are another likely byproduct, produced by hadronic cosmic-ray interactions with ambient debris, though no neutrino counterpart has been reported so far (Adrián-Martínez et al. 2016).

Our reasoning is driven (a) by the modest efficiency \(\lesssim 0.03\) required per event per unit of gravitational-wave energy release; (b) by the frequency of such sources, which is on the order of \(\lesssim 0.001\) of the number of core-collapse supernovae (Abbott et al. 2016b; Marchant et al. 2016), estimated to occur at a rate \(~ 10^5\) Gpc\(^{-3}\) yr\(^{-1}\); (c) by the metal-poor and likely early-epoch environment of the massive star precursors whose associated chemical enrichment of the universe is also of order of \(\epsilon\) of the metal contribution from core-collapse supernovae, namely, \([Z] \sim 0.001\); (d) by the iron-enriched nature of the residual debris around the merging BHs; and (e) by the transient nature of such extragalactic sources. These provide an intriguing basis for the hypothesis that we now explore, namely, that merging BHs potentially provide an environment for accelerating cosmic rays to ultrahigh energies.

In Section 2, we demonstrate that BH mergers would have sufficient luminosity to power the acceleration of cosmic rays to the highest energies. In Section 3, we argue that these systems, as transient sources, can account for the total energy budget of the observed UHECRs and for their distribution in the sky. Section 4 estimates the associated neutrino fluxes and shows that this model is compatible with the current IceCube neutrino sensitivities. We discuss possible sites for UHECR production within this scenario and a possible link with the signal reported by the Fermi-GBM in Section 5.

2. ELECTROMAGNETIC LUMINOSITY

Although no specific literature can be found on the electromagnetic radiation counterparts from the merger of binary stellar BHs, studies of increasing numerical complexity predict such signatures for supermassive BH mergers. The simulations of gas and magnetic fields around the merging systems suggest that the motion of two BHs in a magnetically dominated plasma could generate a magnetosphere and nebular structure similar to those inferred in pulsars, as well as collimated jets (e.g., Milosavljević & Phinney 2005; O’Neill et al. 2009; Palenzuela et al. 2009, 2010; Moesta et al. 2010, 2012; Bode et al. 2012; Giacomazzo et al. 2012; Gold et al. 2014). The level of radiative flux generated is, however, uncertain and subject to strong variabilities according to parameters and unknown structural details of the system.
Most models are in line with the original Blandford–Znajek process (Blandford & Znajek 1977) that extracts the spacetime rotational energy of the BHs to generate a powerful electromagnetic outflow. The same mechanisms can be applied to stellar BHs at the cost of rescaling the BH mass and the magnetic field. A rough estimate of the Poynting flux can then be derived (Lyutikov 2011):

\[ L_{\text{BZ}} = \frac{(GM)^3 B^2}{c^2 R} \sim 3.2 \times 10^{46} \text{ erg s}^{-1} \frac{M_{10}^2 R_{11}^2 R_S}{R}, \]  

where \( M \) is the final BH mass and \( B = B_{11}/10^{11} \) G is the strength of the external magnetic field. We have estimated the orbital radius \( R \) as the Schwarzschild radius \( R_S = 2GM/c^2 \sim 3.0 \times 10^7 M_{100} \text{ cm} \), with \( M_{100} \equiv M/100 M_\odot \).

The magnetic field within the orbit is commonly estimated by assuming that a fraction \( \eta_R \) of the Eddington luminosity is tapped into magnetic luminosity, yielding values of \( B \sim 3 \times 10^6 \text{ GM}_{10}^{3/2} \eta_R^{1/2} (R/R_S)^{-1} \) (e.g., Lyutikov 2011). Recent simulations demonstrate, however, that nonlinear effects should amplify this field by up to two orders of magnitude (Giacomazzo et al. 2012). One could also invoke an \( \omega \)-dynamo process, as for pulsars and magnetars, that would generate fields of strength \( B \sim 10^{12} \text{ G}(P/300 \text{ ms})^{-1} \), with \( P \) as the spin period of the system (Thompson & Duncan 1993; Xu et al. 2002). The seed fields could be anchored to the remains of the accretion disk, the existence of which is proposed, for example, in Perna et al. (2016), that should rotate with period \( P \sim 1-10 \text{ s} \), leading to a dynamo-generated field of \( B \gtrsim 10^{10} \text{ G} \).

A stringent lower limit on the luminosity of any astrophysical outflow can be placed as a necessary condition to accelerate particles to energy \( E \) (Lemoine & Waxman 2009):

\[ L > 10^{52} (E/10^{19} \text{ eV}) Z^{-2} \text{ erg s}^{-1}, \]

with \( Z \) as the charge number of the particle. For a proton composition, this implies that the sources have to be exceptionally bright. Equation (1) suggests that a system like GW150914 should have sufficient power to accelerate particles up to the highest energies, as long as the magnetic field within the orbit can be \( B \gtrsim 10^{11} \text{ G} \).

### 3. A TRANSIENT CANDIDATE SOURCE FOR UHECRs

Above \( E > 10^{19} \text{ eV} \), the observed cosmic-ray flux constrains the source population energy budget to

\[ E_{\text{UHECR}} \rho_0 = 10^{44.5} \text{ erg Mpc}^{-3} \text{ yr}^{-1}, \]

requiring that each individual source supplies an energy

\[ E_{\text{UHECR}} \gtrsim 3.2 \times 10^{53} \text{ erg} \left( \frac{\rho_0}{1 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right)^{-1}, \]

with \( \rho_0 \) as the source population rate at redshift \( z = 0 \). This budget is not easily reached by most astrophysical populations. For BH mergers, the rates inferred by LIGO (Abbott et al. 2016b) imply

\[ E_{\text{UHECR}} \gtrsim 7.9 \times 10^{50} \text{ erg} (\rho_0/400 \text{ Gpc}^{-3} \text{ yr}^{-1})^{-1} \]

and

\[ E_{\text{UHECR}} \gtrsim 1.6 \times 10^{53} \text{ erg} (\rho_0/2 \text{ Gpc}^{-3} \text{ yr}^{-1})^{-1}, \]

for the upper and lower rate limits, respectively. Such energies represent a fraction of <3% of the energy released in gravitational waves by GW150914 (\( E_{\text{gw}} \sim 3.0 M_\odot c^2 \sim 5.4 \times 10^{54} \text{ erg s}^{-1} \)). To achieve such energies, the system would be required to supply a luminosity \( L_{\text{BZ}} \) (Equation (1)) for time spans of 7 hr–2 months. These durations constitute a comfortable fraction of the typical Blandford–Znajek timescale

\[ t_{\text{BZ}} = \frac{M_\odot^2}{L_{\text{BZ}}} \sim 22 M_{100} B_{11}^{-2} \left( R_S/10^2 \text{ yr}^{-1} \right). \]

However, the Blandford–Znajek process would be maintained only as long as the BH accretes after the merger. The relatively long disk accretion time needed by our model is best explained if the disk is sourced by tidal disruption of asteroids or planets. We note that the tidal radius for such a body of mass \( m_{-18} \equiv m/10^{-18} M_\odot \) and size \( r_{\text{km}} \equiv r/1 \text{ km} \) is about \( r \sim 4 \times 10^{11} \text{ cm}(M_{100}/m_{-18})^{1/3} r_{\text{km}} \). The orbital period for the debris is of the order of a day. Such disruptions are plausibly triggered by merger-perturbed orbits of residual asteroid clouds surrounding either or both of the merging BHs.

The absence of multiplets, namely, cosmic-ray events arriving with little angular separation in the sky, can be used to constrain the apparent number density of sources to \( n_0 > 10^{-5} \text{ Mpc}^{-3} \), even if particles are deflected to \( \sim 30^\circ \) (The Pierre Auger Collaboration 2013). The low density of steady candidates: clusters of galaxies (\( 10^{-6} \text{ Mpc}^{-3} \)), FRI-type (\( 10^{-5} \text{ Mpc}^{-3} \)), and FRII-type radio-galaxies (\( 10^{-4} \text{ Mpc}^{-3} \)) is not compatible with these observations. For transient sources, on the other hand, the apparent \( n_0 \) and real \( \rho_0 \) number densities of proton UHECR sources are related via the cosmic-ray arrival time spread \( \delta t \) due to magnetic fields: \( \rho_0 \sim n_0 \delta t \) (Murase & Takami 2009). The time spread is of the order of \( \delta t \sim 10^4 \text{ yrs} \) for a 1° deflection over 100 Mpc, and even rare transient events (e.g., \( \rho_0 = 1 \text{ Gpc}^{-3} \text{ yr}^{-1} \)) could mimic a rather dense population. The rates inferred by the LIGO observations for BH mergers are thus compatible with these observations.

Note that the time delay due to the magnetic deflections will prevent us from observing UHECRs in correlation with the gravitational-wave counterpart of a BH merger (this is valid for any transient source). The only direct evidence of an association between UHECRs and BH mergers can be obtained by the observation of gravitational waves in coincidence with high-energy neutrinos or FRBs, as discussed below.

The statistically significant cosmic-ray excess above energy \( 5.7 \times 10^{19} \text{ eV} \) reported by the Telescope Array (TA) within a 20° radius circle centered at (R.A. = 146.7, decl. = 43.2) (Abbasi et al. 2014) can also be best accommodated with a transient source, due to the absence of a powerful source observed in the direction of this hotspot (N. Renault-Tinacci et al. 2016, in preparation). This BH merger scenario would be well suited to account for this observation.

The chemical composition of cosmic rays reported by the Auger Observatory is not compatible with a light composition at the highest energies (The Pierre Auger Collaboration et al. 2013; Aab et al. 2014a, 2014b). The TA results seem to show the same trend within systematics (Tameda et al. 2011; Pierog 2013; The Telescope Array & Pierre Auger Collaborations 2013). BH mergers stem from the core of massive stars and hence should be surrounded by metal-rich debris from before their collapse. These systems should thus offer a favorable site to produce and accelerate heavy nuclei.

### 4. ASSOCIATED NEUTRINO FLUXES

The secondary neutrino flux from UHECRs accelerated in an individual source at a distance \( D \), with luminosity \( L_{\text{UHECR}} \) can
be estimated as

\[
E_\nu^2 \Phi_\nu \sim \frac{3}{8} f_0 f_\nu \frac{L_{\text{UHECR}}}{4\pi D_z^2} \sim 3.7 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} f_0 f_\nu \times \frac{L_{\text{UHECR}}}{10^{46.5} \text{ erg s}^{-1}} \left( \frac{D_z}{410 \text{ Mpc}} \right)^{-2},
\]

with \( f_\nu \) as the redshift losses (composed of between 0.55 for a source at Hubble distance and 1 for a local source) and \( f_0 \) as the optical depth to neutrino production. For the numerical estimate, as an upper bound to the neutrino flux, we have assumed that the luminosity derived in Equation (1) is entirely tapped into UHECRs. This number is similar to the IceCube single source sensitivity, but is compatible with the absence of the neutrino counterpart reported by ANTARES and IceCube in the direction of GW150014 (Adrián-Martínez et al. 2016), given the usually low value of \( f_\nu \) in astrophysical sources. In the BH merger environment, the radiative and baryonic fields are not expected to be particularly intense. If particle acceleration happens in a jet-like structure created by Blandford–Znajek-type processes, the background fields should resemble those of standard gamma-ray burst scenarios. For instance, for long gamma-ray bursts, \( f_\nu < 10^{-4} \) (Abbasi et al. 2011; He et al. 2012; Li 2012; Hümmer et al. 2012), and for short gamma-ray bursts, the fields are expected to be of lower intensity. The experiments derive an upper bound on the neutrino energy from GW150014 of \( 10^{52} – 54 \) erg. From the inferred energy budget of each source (see Section 3), one can already constrain the optical depth to neutrino production to \( f_\nu < 1 \). A more stringent evaluation of the rate of BH mergers would allow the derivation of a stronger upper bound on \( f_\nu \).

The diffuse all-flavor neutrino flux integrated over the entire source population reads \( E_\nu^2 \Phi_\nu = (3D_H/32\pi) f_\nu f_0 \rho_0 E_{\text{UHECR}} \sim 8.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} f_\nu f_0 \), where \( D_H \) is the Hubble distance and the redshift loss factor \( f_\nu \sim 0.55 \) for a uniform source evolution history and \( f_\nu \sim 2.5 \) for an evolution following the star formation history as in Hopkins & Beacom (2006; Waxman & Bahcall 1999; Fang et al. 2014). This estimate is comparable to the IceCube diffuse sensitivity limit (of the order of \( 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) at \( \sim 10^{17} \text{ eV} \)) and the non-detection of neutrinos implies again an optical depth to neutrino production in the source of \( f_\nu < 1 \).

5. DISCUSSION

We have argued that the production of UHECRs from a population of BH mergers as observed in gravitational waves by LIGO can account, at first order, for all observational constraints of UHECRs (energy budget, global spectrum, arrival directions, composition, and secondary messengers). Detailed simulations and models for acceleration sites would be needed in order to compute the exact composition of particles as a function of energy and the associated spectral features due to energy losses on the radiative and baryonic backgrounds.

It is, however, possible to infer these features from the pulsar model developed in Fang et al. (2012, 2013), as it has been pointed out by Lyutikov (2011) that the magnetospheres of moving BHs resemble those of rotationally powered pulsars, with pair formation fronts and outer gaps, and further out, the formation of a wind-driven cavity possibly surrounded by a nebular region. In this example, UHECR acceleration could happen either in the inner jet region as for gamma-ray bursts, or at the termination shock where the jet encounters the circumstellar medium, if the shock is strong enough, as in Lemoine et al. (2015). The environment of the pulsar could be similar to that described in Piro & Kollmeier (2016) for neutron star mergers, with rather thin optical depths.

One should note also that the present discussion can be applied to supermassive BH mergers and lead to similar results, with the rescaling of the BH mass and orbital magnetic field. We have argued in this work that, because of the transient nature of the source, it will not be possible to make a clear association between the deflected and delayed cosmic rays generated during merger and the emitted GW signal. The observation of correlated neutrino fluxes, that would confirm this model, also seems marginal given the current instrumental sensitivities and the thin source environment. A possible electromagnetic signature of this UHECR model could be fast radio bursts, produced by Poynting flux-driven Alfven wings around circum-BH asteroids. The presence of small bodies orbiting the BH, which would be later disrupted to feed the accretion disk, can indeed be invoked to maintain the accretion and thus the Blandford–Znajek process over a rather long timescale (see Section 3). The timescale for disruption matches the inferred timescale of the acceleration model, and the tidal disruption radius is comparable to the range proposed to account for fast radio bursts in the model of Mottez & Zarka (2014). Note that possible asteroid-generated FRBs could precede the final merger by typically longer orbital timescales, in addition to any similar events associated with the asteroid destruction on timescales of the order of days.

The Fermi satellite Gamma-ray Burst Monitor reported the detection at an \( \sim 3\sigma \)-level of a transient signal of luminosity \( \sim 10^{49} \text{ erg s}^{-1} \) at photon energies \( \sim 0.1–1 \text{ MeV} \) over 1 s that appeared 0.4 s after the gravitational-wave signal. This signal was not detected by any other instrument, and scientific discussion is ongoing (see, e.g., Savchenko et al. 2016). If an external magnetic field of the order of \( \gtrsim 5 \times 10^{12} \text{ G} \) (as commonly observed in pulsars and magnetars) could be generated, Equation (1) implies that the Blandford–Znajek process would extract enough electromagnetic luminosity to account for such an emission. Note that the Eddington luminosity, of the order of \( L_{\text{Edd}} \sim 1.4 \times 10^{46} M_{100} \text{ erg s}^{-1} \), is much lower than the reported luminosity.

The presence of a debris clump of mass comparable to an asteroid, in the vicinity of the BH, is again another possible mechanism for such an event: a similar phenomenon, a slow GRB with an extremely faint optical counterpart, has been suggested to be caused by the disruption of a compact clump falling onto a neutron star (Campana et al. 2011).

We speculate that the early formation inferred for the BH precursors motivates a likely enhancement with overdense early-forming structures. These are likely to be in regions where the first stars may have formed, such as, for example, galactic bulges (Belczynski et al. 2010; Howes et al. 2015).

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