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Cosmological Magnetic Fields from Primordial Kerr-Newman Black Holes

Dan Hooper[a,b,c,*] Aurora Ireland[c,d,†] and Gordan Krnjaic[a,b,c‡]
[a] University of Chicago, Kavli Institute for Cosmological Physics, Chicago IL, USA
[b] University of Chicago, Department of Astronomy and Astrophysics, Chicago IL, USA
[c] Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL, USA and
[d] University of Chicago, Department of Physics, Chicago IL, USA
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The origin of our universe's cosmological magnetic fields remains a mystery. In this study, we consider whether these magnetic fields could have been generated in the early universe by a population of charged, spinning primordial black holes. To this end, we calculate the strength of the magnetic fields generated by this population, and describe their evolution up to the current epoch. We find that extremal black holes in the mass range $M \sim 10^{28} - 10^{36}$ g could potentially produce magnetic fields with present day values as large as $B \sim 10^{-20} - 10^{-15}$ G. While we remain largely agnostic as to the origin of these spinning, charged black holes, we do briefly discuss how new physics may have induced a chemical potential which could have briefly maintained the black holes in an electrically charged state in the early universe.

I. INTRODUCTION

According to the standard paradigm, the magnetic fields present within galaxies and galaxy clusters were generated through the amplification of preexisting, but much weaker magnetic fields through the dynamo mechanism [1–5]. This process is effective, however, only if a non-zero magnetic field is present for the dynamos to amplify. The origin of these magnetic field "seeds," which were present at the onset of structure formation, remains an open question and has generated a great deal of speculation [4, 6–10]. In particular, it has been proposed that primordial magnetic fields could arise within the context of inflation [9, 11–16], or during phase transitions that took place in the early universe [17–23].

The origin of the primordial magnetic field is somewhat obscured by the complicated plasma and magnetohydrodynamics processes that have taken place over cosmic time. One can attempt, however, to constrain the properties of the seed field by studying the magnetic fields found within the voids of the intergalactic medium, where primordial fields could exist in a relatively pristine state. In such environments, the evolution of the magnetic field would be largely driven by the expansion of the universe, leading to the dilution of the field strength as $B \propto a^{-2}$ (corresponding to $\rho_B \propto a^{-4}$), and to the growth of the field's correlation length as $\xi \propto a$.

In this letter, we consider the possibility that primordial magnetic fields may have been generated in the early universe by a subdominant population of primordial black holes. In order to produce a non-zero magnetic field, these black holes must have been both spinning and electrically charged, so we use the formalism of the Kerr-Newman metric. In our scenario, this population is temporarily charged in the early universe due to a nonzero chemical potential, which eventually relaxes to zero at which point the black holes discharge. Upon discharge, the Kerr-Newman magnetic fields evolve according to Hubble expansion and the (now neutral) black holes constitute a present day dark matter abundance. While such a scenario is admittedly quite speculative and involves some very exotic elements, we find that astrophysically interesting magnetic fields could have potentially been generated by such objects.

II. KERR-NEWMAN BLACK HOLES

Generating a magnetic field requires both an electromagnetic current and a departure from spherical symmetry. For this reason, we are interested here in black holes that are both charged and rotating. Such Kerr-Newman black holes are entirely characterized by their mass, M, angular momentum, J, and charge, Q. In Boyer-Lindquist coordinates, the geometry associated with such an object is described by the following line element [24–26]:

$$ds^2 = -\frac{\Delta}{\rho^2}(dt - \alpha \sin^2\theta \, d\phi)^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 + \frac{\sin^2\theta}{\rho^2}\left[(r^2+\alpha^2)d\phi - \alpha dt\right]^2 , \tag{1}$$

where $\alpha = J/M$, and we have defined

$$\rho^2 = r^2 + \alpha^2\cos^2\theta, \quad \Delta = r^2 + \alpha^2 - \frac{2Mr}{M_{\rm Pl}^2} + \frac{Q^2}{M_{\rm Pl}^2}, \tag{2}$$

and $M_{\rm Pl} = 1.22 \times 10^{19}$ GeV is the Planck mass. The charge and angular momentum of a black hole are constrained to lie within the following domain:

$$\alpha^2 M_{\rm Pl}^2 + Q^2 \leq \frac{M^2}{M_{\rm Pl}^2} \, . \tag{3}$$

* ORCID: http://orcid.org/0000-0001-8837-4127
† ORCID: https://orcid.org/0000-0002-3004-0930
‡ ORCID: http://orcid.org/0000-0001-7420-9577

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From the metric, we see that the Kerr-Newman black hole has two horizons located at

$$r_\pm = \frac{1}{M_{\rm Pl}^2}\left(M \pm \sqrt{M^2 - \alpha^2 M_{\rm Pl}^4 - Q^2 M_{\rm Pl}^2}\right). \quad (4)$$

Integrating over the angular volume element evaluated on the $r = r_+$ hypersurface yields the area of the event horizon

$$A = 4\pi\,(r_+^2 + \alpha^2). \quad (5)$$

From the Killing vector associated with the event horizon, the surface gravity can be written as [26]

$$\kappa = \frac{2\pi}{A}(r_+ - r_-). \quad (6)$$

These two quantities are related to a black hole's temperature and entropy as follows [27]:

$$T_{\rm BH} = \frac{\kappa}{2\pi} = \frac{r_+ - r_-}{4\pi(r_+^2 + \alpha^2)} \quad (7)$$

$$S_{\rm BH} = \frac{A}{4} = \pi(r_+^2 + \alpha^2). \quad (8)$$

These expressions, in conjunction with the fact that the mass of a black hole can be identified with energy, yields the first law of black hole thermodynamics:

$$dM = \frac{M_{\rm Pl}^2}{8\pi}\,\kappa\,dA + \Omega\,dJ + \Phi\,dQ, \quad (9)$$

where Ω and Φ are the angular velocity and the electrostatic potential of the black hole. Note that the quantities κ (and hence $T_{\rm BH}$), Ω, and Φ are constant over the horizon. In order to obtain explicit forms for Ω and Φ in the context of a Kerr-Newman black hole, we need to take the differential of the area given in Eq. (5). After some algebra, we can write

$$\frac{M_{\rm Pl}^2}{8\pi}\,\kappa\,dA = \frac{r_+^2 dM}{r_+^2 + \alpha^2} - \frac{r_+ Q dQ}{r_+^2 + \alpha^2} - \frac{M\alpha d\alpha}{r_+^2 + \alpha^2}. \quad (10)$$

Substituting $-\alpha M d\alpha = -\alpha dJ + \alpha^2 dM$ and inserting the explicit form for κ, we arrive at the following expression:

$$dM = \frac{M_{\rm Pl}^2}{4}\,T_{\rm BH}\,dA + \frac{\alpha dJ}{r_+^2 + \alpha^2} + \frac{r_+ Q dQ}{r_+^2 + \alpha^2}. \quad (11)$$

Comparing this to Eq. (9), we can determine the black hole's angular velocity and electrostatic potential:

$$\Omega = \frac{\alpha}{r_+^2 + \alpha^2}, \quad \Phi = \frac{r_+ Q}{r_+^2 + \alpha^2}. \quad (12)$$

III. GENERATING COSMOLOGICAL MAGNETIC FIELDS

We begin by considering an isolated black hole whose mass, angular momentum, and charge are not appreciably evolving with time, hence neglecting the possible effects of Hawking evaporation and accretion. This stationary geometry is described by the Kerr-Newman metric given in Eq. (1). To determine the E and B fields, we need both the metric and the vector potential A_μ, which satisfy [26]

$$A_\mu dx^\mu = -\frac{Qr}{r^2 + \alpha^2\cos^2\theta}\left(dt - \alpha\sin^2\theta\,d\phi\right). \quad (13)$$

Using the field strength, $F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$, the fields are given by

$$\vec{E} = \frac{Q(r^2 - \alpha^2\cos^2\theta)}{\rho^4}\,\hat{r} - \frac{2Q\alpha^2\cos\theta\sin\theta}{\rho^4}\,\hat{\theta}, \quad (14)$$
$$\vec{B} = \frac{Q\alpha}{r}\left[\frac{2(\alpha^2 + r^2)\cos\theta}{\rho^4}\,\hat{r} + \frac{(r^2 - \alpha^2\cos^2\theta)\sin\theta}{\rho^4}\,\hat{\theta}\right].$$

Note that the E_ϕ and B_ϕ components are both vanishing, since we've taken the black hole to be rotating in the $\hat{\phi}$ direction. Also note that in the $r \to \infty$ limit, these fields have the expected asymptotic forms:

$$\lim_{r\to\infty} \vec{E} = \frac{Q}{r^2}\,\hat{r} + \mathcal{O}\left(\frac{1}{r^3}\right), \quad (15)$$
$$\lim_{r\to\infty} \vec{B} = \frac{Q\alpha}{r^3}\left(2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta}\right) + \mathcal{O}\left(\frac{1}{r^4}\right).$$

In considering the case of an isotropic population of black holes,[1] it will be useful to have an expression for the magnetic field of a single black hole averaged over a sphere of radius $R > r_+$. We adopt the following volume-averaged convention[2]:

$$\langle\vec{B}\rangle = \frac{1}{V}\int_V d^3x\,\vec{B}\,, \quad (16)$$

where $V = 4\pi R^3/3$ is the volume of the sphere over which we are averaging. Starting from Eq. (15) and omitting the algebraic details, the volume-averaged magnetic field magnitude can be written as

$$\langle B\rangle = \frac{3Q}{R^2}\left[\left(1 + \frac{R^2}{\alpha^2}\right)\tan^{-1}\left(\frac{\alpha}{R}\right) - \frac{R}{\alpha}\right]. \quad (17)$$

In the $\alpha \ll R$ limit, the average magnetic field reduces to $\langle B\rangle \approx 2Q\alpha/R^3$. This limit will be applicable throughout our entire parameter space of interest.

The primordial magnetic field is also characterized by a correlation length ξ, which governs the extent to which diffusion and damping will suppress any magnetic fields that are generated by black holes in the early universe.

[1] A possible objection to this scenario is that the black holes might act as an ensemble of magnetic dipoles which interact to form domains of some characteristic scale. This will not be applicable in this case, however, as we will consider black hole number densities which are sufficiently small such that no more than one black hole will be present in a given Hubble radius at early times.

[2] We have chosen this convention since it admits a closed form expression for the average field. We have confirmed numerically that our definition coincides with the RMS average value, $B_{\rm RMS}^2 = \frac{1}{V}\int d^3x\,\vec{B}^2$, up to an $\mathcal{O}(1)$ factor.

On scales greater than the magnetic diffusion length, diffusive effects can be neglected, so the comoving field is frozen and ξ grows linearly with the scale factor of the universe. Although ξ is formally defined using the Fourier transform of the magnetic energy density, here we use a simpler measure of the correlation length, defining ξ as the average distance between neighboring primordial black holes:

$$\xi \sim \left(\frac{3}{4\pi n_{\rm BH}}\right)^{1/3} = \left(\frac{45}{2\pi^3 g_\star(T)}\frac{M}{f_{\rm BH}T^4}\right)^{1/3}, \tag{18}$$

where $f_{\rm BH} = M n_{\rm BH}/\rho_R(T)$ is the energy fraction in black holes relative to that in radiation at the time of magnetogenesis and $g_\star(T)$ is the number of effective relativistic degrees of freedom at temperature T.

Once a magnetic field is generated at some initial temperature, T_i, there are several processes which can affect its evolution, including small scale damping, diffusion, and the expansion of the universe [5, 7]. We will make the assumption that the initial correlation length is sufficiently large that we do not need to account for the former effects, and focus solely on the impact of Hubble expansion. We will later show that this assumption is self-consistent for all parameter space of interest. In an expanding universe, the magnetic field redshifts as $B \propto a^{-2}$, while the correlation length grows as $\xi \propto a$. These scalings are manifest when writing B and ξ in terms of temperature:

$$B(T) = B_i\left(\frac{T}{T_i}\right)^2\left[\frac{g_{\star,S}(T)}{g_{\star,S}(T_i)}\right]^{2/3} \tag{19}$$

$$\xi(T) = \xi_i\left(\frac{T_i}{T}\right)\left[\frac{g_{\star,S}(T_i)}{g_{\star,S}(T)}\right]^{1/3}, \tag{20}$$

where $g_{\star,S}(T)$ is the effective number of degrees-of-freedom in entropy, and the initial values at magnetogenesis, B_i and ξ_i, can be related to black hole parameters using Eqs. (17) and (18), with $R = \xi_i$. Defining the following dimensionless parameters:

$$\alpha_\star \equiv \alpha\frac{M_{\rm Pl}^2}{M} = J\frac{M_{\rm Pl}^2}{M^2}, \quad Q_\star \equiv Q\frac{M_{\rm Pl}}{M}, \tag{21}$$

the magnetic field from Eq. (19) can be written as

$$\langle B_0\rangle = \frac{4\pi^3\alpha_\star Q_\star f_{{\rm BH},i}\, g_\star(T_i)T_i^2T_0^2M}{45M_{\rm Pl}^3}\left[\frac{g_{\star,S}(T_0)}{g_{\star,S}(T_i)}\right]^{2/3}, \tag{22}$$

where present day values are denoted by a "0" subscript, $T_0 = 2.725$ K is the CMB temperature, and $f_{{\rm BH},i}$ is the black hole energy fraction at T_i. In order to express this in terms of current observables, we apply the conservation of entropy:

$$\frac{g_{\star,S}(T_0)}{g_{\star,S}(T_i)} = \left(\frac{a_iT_i}{a_0T_0}\right)^3, \tag{23}$$

where $a_{i,0}$ is the scale factor at the corresponding epoch. Noting also that the initial black hole energy density at magnetogenesis satisfies

$$\rho_{\rm BH}(T_i) = f_{{\rm BH},i}\left(\frac{\pi^2 g_\star(T_i)T_i^4}{30}\right) = \Omega_{\rm BH}\rho_c\left(\frac{a_0}{a_i}\right)^3, \tag{24}$$

where $\Omega_{\rm BH} \equiv \rho_{\rm BH}/\rho_c$ is the present day energy density in black holes relative to the critical density $\rho_c \approx 4\times10^{-47}$ GeV^4, we can rewrite Eq. (22) as

$$\begin{aligned}\langle B_0\rangle &= \frac{8\pi\alpha_\star Q_\star\Omega_{\rm BH}\rho_c M}{3M_{\rm Pl}^3}\frac{T_i}{T_0}\left[\frac{g_{\star,S}(T_i)}{g_{\star,S}(T_0)}\right]^{1/3} \\ &\approx 6\times10^{-16}\,{\rm G}\left(\frac{Q_\star\alpha_\star}{0.5}\right)\left(\frac{\Omega_{\rm BH}}{0.01}\right)\left(\frac{M}{M_\odot}\right)\left(\frac{T_i}{\rm GeV}\right),\end{aligned} \tag{25}$$

where in the last line we have used $g_\star = g_{\star,S} = 73$ at $T_i = 1$ GeV. Note that in terms of $\alpha_\star$ and $Q_\star$, the extremality condition is $\alpha_\star^2 + Q_\star^2 \leq 1$, which implies $\alpha_\star Q_\star \leq 0.5$. Similarly, combining Eqs. (18) and (20), the present day correlation length can be written as

$$\xi_0 = \frac{1}{T_0}\left(\frac{45M}{2\pi^3 g_\star(T_i)\, f_{{\rm BH},i}\, T_i}\right)^{1/3}\left[\frac{g_{\star,S}(T_i)}{g_{\star,S}(T_0)}\right]^{1/3}. \tag{26}$$

Using Eqs. (23) and (24), we obtain

$$\xi_0 = \left(\frac{3M}{4\pi\,\Omega_{\rm BH}\rho_c}\right)^{1/3} \approx 0.6\,{\rm kpc}\left(\frac{0.01}{\Omega_{\rm BH}}\right)^{1/3}\left(\frac{M}{M_\odot}\right)^{1/3}. \tag{27}$$

Naively applying Eq. 25, it might appear that arbitrarily strong magnetic fields could be generated by black holes at sufficiently high temperatures, $T_i \gg$ GeV. Black holes of a given mass, however, can only be formed once $M > M_H$, where M_H is the mass contained within the horizon:

$$M_H = \frac{M_{\rm Pl}^2}{2H_i} \approx 0.06M_\odot\left(\frac{\rm GeV}{T_i}\right)^2\left(\frac{73}{g_\star(T_i)}\right)^{1/2}. \tag{28}$$

By evaluating Eq. (25) at M_H, we find the following upper limit for the magnetic field strength that could be generated by spinning, charged black holes:

$$\langle B_0\rangle_{\rm max} \approx 4\times10^{-17}\,{\rm G}\left(\frac{Q_\star\alpha_\star}{0.5}\right)\left(\frac{\Omega_{\rm BH}}{0.01}\right)\left(\frac{\rm GeV}{T_i}\right). \tag{29}$$

Alternatively, in terms of the horizon mass, this maximum magnetic field can be written as

$$\langle B_0\rangle_{\rm max} \approx 1.5\times10^{-16}\,{\rm G}\left(\frac{Q_\star\alpha_\star}{0.5}\right)\left(\frac{\Omega_{\rm BH}}{0.01}\right)\left(\frac{M_H}{M_\odot}\right)^{1/2}. \tag{30}$$

IV. POTENTIALLY VIABLE PARAMETER SPACE

In Fig. 1, we plot the strength and correlation length of the magnetic fields generated by primordial black holes, for the optimal case of $Q_\star\alpha_\star = 0.5$. Also shown in this figure are the constraints on this parameter space from gravitational microlensing surveys [28–31], gravitational wave observations [32–34], and from the impact of accretion on the CMB [35] (for reviews, see Refs. [36, 37]).

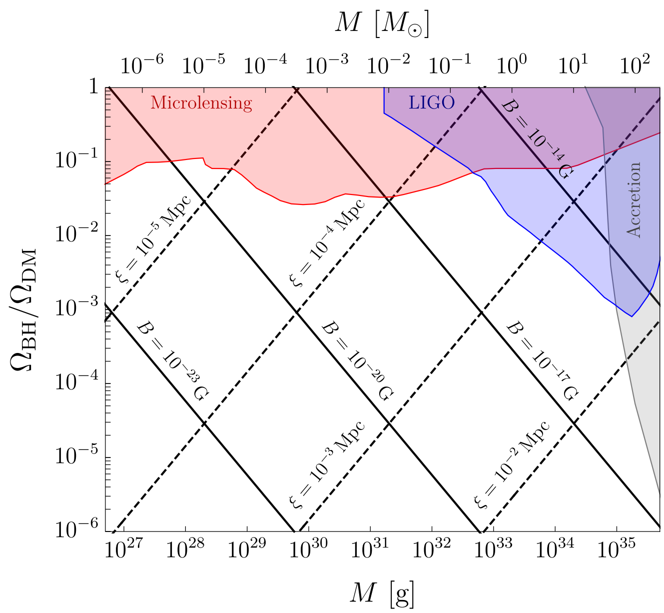

FIG. 1. The present day strength and correlation length of the magnetic fields generated by primordial black holes, for the optimal case of $Q_\star\alpha_\star = 0.5$. Also shown are the constraints on this parameter space from gravitational microlensing surveys [28–31], gravitational wave observations [32–34], and from the impact of accretion [35]. Astrophysically relevant magnetic fields ($B \gtrsim 10^{-20}$ G) could be generated by primordial black holes in the mass range of $M \sim 10^{28}$–10^{36} g without violating existing constraints. For non-extremal black holes, the strength of the resulting magnetic fields would be smaller than those shown by a factor of $Q_\star\alpha_\star/0.5$.

From this figure, we see that astrophysically relevant magnetic fields ($B \gtrsim 10^{-20}$ G) could potentially have been generated by primordial black holes with masses in the range of $M \sim 10^{28} - 10^{36}$ g, without violating any existing constraints. Throughout this mass range, once the black holes discharge, their Hawking radiation is negligible, so this population constitutes a faction of the dark matter today [38, 39].

In this parameter space of interest, the correlation length of the present day magnetic field falls in the range of $\xi \sim 10^{-6} - 10^{-1}$ Mpc. Across this range of values, the magnetic fields are predicted to survive the effects of magnetic dissipation and diffusion [5, 6, 40, 41]. More explicitly, in order to avoid early magnetic dissipation the present day field should satisfy [42]

$$\xi_0 \gtrsim 10^{-7}\,\mathrm{Mpc}\left(\frac{\langle B_0\rangle}{10^{-15}\,\mathrm{G}}\right) . \tag{31}$$

This condition is easily fulfilled for the relevant parameter space in Fig. 1, corresponding to magnetic fields with $B \sim 10^{-20} - 10^{-15}$ G and $\xi \gtrsim 10^{-12} - 10^{-7}$ Mpc. Thus, in this regime we are justified in considering only Hubble expansion in translating the early universe field to its present day value.

V. CHARGED BLACK HOLES AND CHEMICAL POTENTIALS

Thus far, we have remained agnostic regarding the origin of the Kerr-Newman black holes. Of course it's very difficult to create black holes with geometrically significant charge in the early universe. In a cosmological setting, any net charge would be quickly neutralized by the surrounding plasma, which we assume has a compensating charge to maintain the charge neutrality of the universe. Even if one were to consider a charged black hole in a vacuum, its charge is expelled exponentially quickly through Hawking radiation [43]. The existence of a population of charged black holes would thus require the introduction of new physics.

The Hawking radiation of electrically neutral black holes is symmetric with respect to the production of particles and anti-particles. By contrast, charged black holes preferentially radiate particles with the same sign charge as that of the black hole, an effect which can be parameterized in terms of a chemical potential at the event horizon. Note that the electromagnetic potential, A_μ, of the Kerr-Newman black hole from Eq. (13) sources a chemical potential for charged particles through its lagrangian coupling to a particle of charge q produced at the horizon: $\mathcal{L} \supset -qA_\mu J^\mu_{\rm EM}$. Since the time-like component couples to the charge density $J^0_{\rm EM}$, we can identify the combination $-qA_0|_{r_+}$ with a chemical potential, μ_q:

$$\mathcal{L} \supset -qA_0 J^0_{\rm EM} \equiv \mu_q J^0_{\rm EM} \,. \tag{32}$$

Alternatively, consider the spectrum of particle emission from a Kerr-Newman black hole, which follows a thermal distribution [38, 44]:

$$dN \sim \frac{d\omega}{\exp\left[(\omega - m\Omega - q\Phi)/T_{\rm BH}\right] \mp 1} \,, \tag{33}$$

where ω and m are the energy and angular momentum of the emitted particle, Ω and Φ are the angular velocity and electrostatic potential of the black hole from Eq. (12), and the $\mp$ refers to bosons and fermions, respectively. We can identify $\mu_q \equiv q\Phi$ as a chemical potential, biasing the emission of particles whose charge has the same sign as that of the black hole. Note that $-A_0|_{r_+}$ is identified with Φ, which matches the approach from Eq. (32). From this expression, we also see that $m\Omega$ acts in a similar manner, leading the black hole to preferentially expel particles whose angular momentum is aligned with that of the black hole. Thus, the black hole will shed both quantities as it evaporates, evolving towards a neutral, non-rotating state.

Just as the intrinsic chemical potential of the Kerr-Newman black hole allows it to shed its charge, one can imagine charging up a black hole (or maintaining a black hole in a charged state) by means of an external chemical potential. If such a chemical potential is greater than that of the black hole itself, then the black hole will build up charge until it reaches an extremal state.

As a proof of principle, one possible mechanism for realizing such a chemical potential involves a new scalar field ϕ derivatively coupled to the electromagnetic current via

$$\mathcal{L} \supset \frac{1}{\Lambda}\partial_\mu \phi J^\mu_{\rm EM}\,, \tag{34}$$

where Λ is the scale at which heavy particles have been integrated out to generate this operator. If ϕ is initially displaced from the origin and begins rolling in the early universe, its time derivative will source an effective chemical potential for charged particles, $\mu_\phi \equiv \dot{\phi}$, leading the black hole to preferentially absorb particles with charge of a particular sign. Magnetic field generation will occur during the period in which the external chemical potential is active because the scalar field is rolling. Once ϕ stops rolling at temperature T_i, the chemical potential will vanish and the black hole will quickly expel its charge, thereby returning to a neutral state. However, building a realistic model that realizes Eq. (34) and suffices for charging up the black holes is beyond the scope of this letter and is left for future work.

VI. SUMMARY AND CONCLUSIONS

In this letter, we have studied the possibility that cosmological magnetic fields may have been generated in the early universe by a population of primordial Kerr-Newman black holes. We find that black holes near extremality ($\alpha_\star Q_\star \sim 0.5$) in the mass range of $M \sim 10^{28} - 10^{36}$ g would be capable of producing present day fields that are as large as $B \sim 10^{-15}$ G. These fields could have seeded larger galactic and intergalactic fields through the dynamo mechanism.

In order to generate a magnetic field in the early universe, the black holes in this scenario must be both spinning and electrically charged. Throughout most of our analysis, we have remained agnostic as to the origin of these Kerr-Newman black holes. While it is straightforward to create spinning black holes through the mergers of an initial population of Schwarzschild black holes [45], it is more challenging to explain how these black holes acquire an appreciable net electric charge in the early universe. As discussed in Sec. V, one possibility involves a rolling scalar field which generates a dynamical chemical potential for a charged particle species, thereby biasing the charge distribution of Hawking radiation and the net flow of charge into the black holes. We leave the model building that concretely realizes such a scenario for future work.

Finally, we note that this scenario predicts a nontrivial relationship between the primordial magnetic field parameters and the merger rate for the progenitor black hole population. Since the initial black hole separation distance and mass distribution determines both the binary merger rate and the correlation length of the resulting magnetic field, it may be possible to identify a smoking gun signature from a large sample of merger events and an observation of the spatial morphology of the primordial magnetic fields. We also leave this analysis for future work.

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