Can Primordial Magnetic Fields Seeded by Electroweak Strings Cause an Alignment of Quasar Axes on Cosmological Scales?

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The decay of nontopological electroweak strings may leave an observable imprint in the Universe today in the form of primordial magnetic fields. Protogalaxies preferentially tend to form with their axis of rotation parallel to an external magnetic field, and, moreover, an external magnetic field produces torque which tends to align the galaxy axis with the magnetic field. We demonstrate that the shape of a magnetic field left over from two looped electroweak strings can explain the observed nontrivial alignment of quasar polarization vectors and make predictions for future observations.

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Introduction.—Recently, Hutsemékers *et al.* collected linear polarization data of 355 quasars (see Fig. 13 in Ref. [1]). They observed that (i) the polarization vector of quasars are somewhat aligned over large (cosmologically interesting) volumes of space and (ii) the angle of these vectors rotate coherently with increasing redshift with a probability of less than 0.1% of such an alignment occurring by chance. They claim these two observations seem unlikely to be attributable to either natural contamination or unaccounted instrumental bias. Instead, the effect appears to be cosmological.

The direction of the optical polarization vector can be attributed to the physical orientation of the quasar itself [2–4]. Any model that explains the coherent alignment of quasars on such scales should also address the rotation through $\sim 240°$ observed in the sample. This feature cannot be easily accommodated in generic models.

We propose that the orientation of these quasars is caused by a magnetic field left over from two linked loops of electroweak strings. From the time of the electroweak phase transition (EWPT) to today, magnetic field lines seeded by these strings act as a background magnetic field at the time of quasar formation. We fit the alignment data and find that the electroweak string loops can explain this alignment very well.

Quasar structure.—At a quasar's center lies a supermassive black hole surrounded by an accretion disk. The central regions of quasars emit massive amounts of continuum radiation. From the accretion disk, a warm wind arises perpendicular to the plane of the accretion disk over a narrow range of radii. Radiation pressure accelerates this wind radially away from the continuum source, causing a funnel-shaped outflow [2]. A subclass of quasars, broad absorption line quasars comprise $\sim 10\%$ of all quasars. These objects (which were given observational preference in Ref. [1]) are observed as such due to their orientation to us. The polarized radiation from broad absorption line quasars originates from the conical shell surrounding the quasar's center. Flux from the continuum source at the center of the quasar is Thompson scattered off the shell [2]. In Refs. [3,4], the authors report that the direction of polarization from type 1 quasars tends to be parallel with the axis of the quasar host. Type 1 quasars on average tend to have broad absorption lines as well [5].

Electroweak cosmic strings in the early Universe.—The early Universe very likely went through a number of phase transitions that gave rise to various topological defects via the Kibble mechanism. While the electroweak standard model gauge group $SU(2)_L \times U(1)_Y$ does not contain nontrivial topology, it does contain so-called embedded defects, most notably electroweak cosmic strings [6–8]. In the minimal version of the standard model (for the physical values of the relevant parameters weak mixing angle and Higgs boson mass), electroweak cosmic strings are not stable configurations [9–11]. It is very unlikely that they exist today, but one cannot avoid their formation and a subsequent decay. Cosmic strings produced during the EWPT exist as closed loops or are infinitely long [12]. Cosmic strings also contain small scale structure in the form of wiggles [13–15]. We consider the case of two electroweak strings that are initially linked. The strings each carry Z lines of magnetic flux parallel to the direction of the string [12]. A mechanism that may cause strings to decay is through the creation of a monopole-antimonopole pair. Tension in the string pulls the monopole-antimonopole pair apart. The Z magnetic flux lines become frozen in the highly conductive plasma of the early Universe, and a linked magnetic field remains [12,16]. The magnetic field is carried by the expansion of the Universe and today exists on cosmological scales. Requiring $\nabla \cdot \vec{B} = 0$ in an Abelian theory implies that parallel magnetic field lines repel [12]. Our final field configuration is two spread-out, interconnected loops of a magnetic field (Fig. 1).

Form of the resulting B field.—We assume the shape of the magnetic field left over from an electroweak string to be a circle of radius R. The magnetic field strength should be constant around the string and go to zero infinitely far

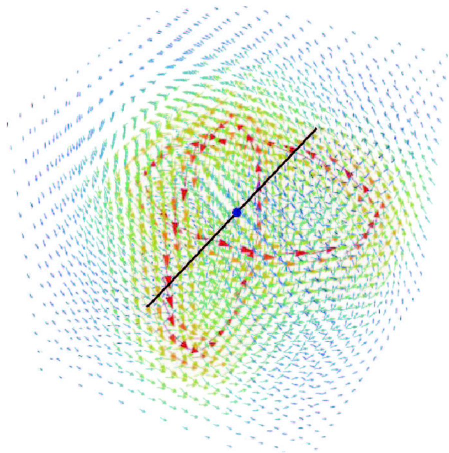

FIG. 1 (color online). The configuration of the magnetic from Eq. (1). The locations of the $A1$-$A3$ axis (straight thick line) and Earth (dot on the $A1$-$A3$ axis) are drawn in. Today each loop of the magnetic field has a characteristic scale on the order of Gpc. The strongest alignment effect is predicted at the intersection of the line of sight with linked loops, i.e., four peaks in the data (see Fig. 2 for predictions and Fig. 3 for the actual data).

away from the string. A single field loop can be described by $\vec{B} = \frac{B_0}{R}\exp[-\sqrt{z^2 + (\rho - R)^2}]\hat{\phi}$. For two magnetic field loops, we place one loop in the $x = 0$ plane and a second loop in the $z = 0$ plane. The loops' centers are separated a distance d, where $0 < d < 2R$:

$$\begin{aligned}\vec{B} = \frac{B_0}{R}[(-\{y + d\} \\ &\times \exp\{-\sqrt{z^2 + [\sqrt{x^2 + (y + d)^2} - R]^2}\})\hat{x} \\ &+ (x\exp\{-\sqrt{z^2 + [\sqrt{x^2 + (y + d)^2} - R]^2}\} \\ &- z\exp\{-\sqrt{x^2 + (\sqrt{y^2 + z^2} - R)^2}\})\hat{y} \\ &+ \{y\exp[-\sqrt{x^2 + (\sqrt{y^2 + z^2} - R)^2}]\}\hat{z}]. \end{aligned} \quad (1)$$

Effects of magnetic flux on quasar orientation.—To explain the effect of a magnetic field on quasar host orientation, we assume a matter-dominated universe from the present back to recombination (at $z \sim 10^3$) and a radiation-dominated universe from recombination back to the EWPT. Assuming the EWPT occurs at $t \sim 10^{-11}$ s and recombination at $t \sim 10^{13}$ s, the EWPT occurs at a redshift of $z \sim 10^{12}$. A magnetic field loop on the Gpc scale today ($R_0 \sim 1$ Gpc) implies the loop was of scale $R_{\rm rec} \sim 1$ Mpc at recombination and $R_{\rm EW} \sim 10^{-6}$ pc $\sim 10^{10}$ m at the EWPT. While this scale is larger than the causally connected universe at the EWPT, there is no reason that such a string should be unphysical as extended topological defects naturally have superhorizon structures. Strings themselves also have small structural irregularities (wiggles) that exist down to a scale $\ell \sim \alpha t$. The parameter α is not known, but simulations suggest at most $\alpha \lesssim 10^{-3}$ [15]. By taking $\alpha \sim 10^{-3}$, the wiggles have a characteristic length scale $\ell \sim 3$ μm at the EWPT and $\ell \sim 10^{-7}$ pc at the time of galaxy or quasar formation. The magnetic field, therefore, would contain wiggles that may be relevant for seeding galaxy formation.

The Lorentz force perturbs the smooth background density of the early Universe $\rho_b(t)$ inducing density perturbations and peculiar velocities $\vec{v}(\vec{x}, t)$ within the fluid. It is argued in Ref. [17] that a somewhat inhomogeneous magnetic field could modulate galaxy formation in the cold dark matter picture by giving the baryons a streaming velocity relative to dark matter.

Assuming locally (on scales relevant to quasar formation) that the average magnetic field lies only in the z direction ($\langle B_x\rangle = \langle B_y\rangle = 0, \langle B_z\rangle \neq 0$), the linearized magnetohydrodynamic Euler's equation [18,19] to zeroth order in small quantities becomes

$$\frac{\partial \vec{v}}{\partial t} = -\frac{\dot{a}}{a}\vec{v} - \frac{GM}{ar^2}\hat{r} - \frac{\mu_0}{4\pi a}\frac{\rho}{\rho_b}|B_b|\exp(-2Ht)v_\perp\hat{\phi}, \quad (2)$$

where $v_\perp$ is the component of peculiar velocity perpendicular to the magnetic field. To compare the gravitational contribution to the magnetic contribution in Eq. (2), we assume a spherical collapsing protogalaxy of uniform density. Defining Ξ as the ratio of the strength of the gravitational term to the Lorentz term, we find

$$\Xi = \frac{\frac{4}{3}\pi G\rho_b r}{10^{-7}|B_b|v_\perp}. \quad (3)$$

By taking a present baryon density of 3.8×10^{-28} kg m^{-3} and background magnetic field strength $|B_b| = 10^{-12}$ G, the ratio Ξ for a protogalactic cloud at $z = 9$ with temperature $T = 10$ K will be $\Xi_{H^+} = 80$ kpc^{-1} for H^+ ions in the cloud and $\Xi_{e^-} = 1.9$ kpc^{-1} for electrons in the cloud. In the central regions of the cloud this ratio becomes $\Xi_{H^+} = 2.46 \times 10^{-2} LY^{-1}$ and $\Xi_{e^-} = 5.78 \times 10^{-4} LY^{-1}$. This implies that the inner regions of a collapsing cloud (including scales comparable to the size of quasars) are dominated by effects from the Lorentz force, while the outer regions of the collapsing cloud are more influenced by effects of gravitational contraction.

The angular momentum of a quasar will most likely point parallel to the average direction of the background magnetic field. There is no guarantee that a specific quasar will not have changed its orientation since formation, but because every quasar (in the immediate vicinity) formed in a similar background, we still expect some trends in the data. We do expect the average quasar polarization direction and magnetic field to be parallel.

An alternative mechanism that could complement the previously mentioned mechanism of alignment of quasar hosts is that the magnetic field physically flips the quasar host itself. Using elementary mechanics, we perform an order of magnitude calculation to determine a typical flip time for a galaxy. We model a quasar as a solid disk with moment of inertia I and magnetic dipole moment $\vec{m}$ in an external magnetic field $\vec{B}$. The work necessary to rotate a quasar about its diameter is written as $W = \int \tau d\theta = \int mB \sin(\theta) d\theta$. The work necessary to rotate a quasar through an angle of 90° can also be described as a change in kinetic energy, so that we may say $W = mB = \Delta KE = \frac{1}{2} I \Delta\omega^2$. Recalling that torque can be described by $\tau = I\frac{\Delta\omega}{\Delta t}$, we find the typical flip time is $\Delta t = \sqrt{2I/mB}$. Using fiducial values of $10^{11} M_{\odot}$, 15 kpc, 10^{63} J/T, and 10^{-12} T for a quasar host's mass, radius, dipole moment, and strength of the external magnetic field, respectively, we find that the flip time for a quasar is $\sim 1.5 \times 10^8$ years. This time scale is significantly less than the age of the Universe at $z = 3$, allowing the quasars sufficient time to align their axes with the external magnetic field.

Here we have presented two effects that work synergistically. Quasar hosts prefer to form with their rotational axis parallel to the external magnetic field, and the external magnetic field will tend to align the quasar axis with itself even if the two axes are not aligned initially.

Matching the model with observations.—A pattern of alignment is apparent in Fig. 13 from Ref. [1]. The authors of Ref. [1] notice an especially high degree of alignment within two regions of space containing 183 of the 355 observed quasars lying in roughly opposite directions on the sky referred to as the $A1$-$A3$ axis [20]. Within the $A1$-$A3$ axis the authors of Ref. [1] also observe a varying degree of alignment among the quasars as shown in Fig. 3.

Our model allows a rotation through $\sim 270°$ to match with observation. If we lie near the center of two linked strings, we could observe a rotation through $\sim 135°$ looking in opposite directions towards the North Galactic Pole (NGP) and South Galactic Pole (SGP). We set the $A1$-$A3$ axis to lie along the y axis of Eq. (1). The magnetic field along that line takes the form of Eq. (4). For generality, we also include the term s:

$$\vec{B} = -\frac{B_0}{R}[(y+s)+d]\exp[-||(y+s)+d|-R|]\hat{x} + \frac{B_0}{R}(y+s)\exp[-||y+s|-R|]\hat{z}. \quad (4)$$

A background magnetic field may not automatically guarantee an alignment effect, but we do expect a higher degree of alignment in regions of stronger magnetic field. It is interesting to compare the four peaks from our model in Fig. 2 to the four regions of high local statistic value in Fig. 3. We do not expect the plots to *exactly* coincide as Fig. 2 plots the magnetic field strength along a line while regions $A1$ and $A3$ are volumes of space. Setting the $A1$-$A3$ axis along the y axis projects the observed polarization vectors into the x-z plane. From Eq. (4) we expect the average polarization angle to be

$$\theta = \frac{180}{\pi}\arctan\left[\frac{(y+s+d)\exp[-||y+s+d|-R|]}{(y+s)\exp[-||y+s|-R|]}\right] + b, \quad (5)$$

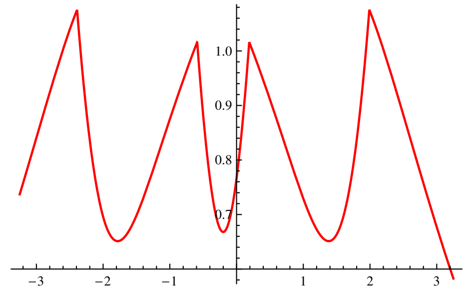

FIG. 2 (color online). The magnitude of the magnetic field described by Eq. (4). Compare this figure to Fig. 3, which shows the degree of alignment along the $A1$-$A3$ axis from Ref. [1]. For this plot we chose $B = 1$, $R = 1.29$, $d = 1.8$, and $s = -0.7$.

where the term b allows for an overall shift in angle. Minimizing the chi-square value, we find the parameters in Eq. (5) best fit by $s = -0.70$, $d = 1.80$, $R = 1.29$, and $b = 324$. Because of the form of the arctan function, we plot Fig. 4 with $b = 324$ for redshift bins centered on $z = -2.75$ through $z = 0.25$ and $b = 144$ for redshift bins centered on $z = 0.75$ through $z = 2.75$. The authors of Ref. [1] propose a best fit of $\bar{\theta} = 268 - 42z$, corresponding to a chi-square value of 98.4. Our model of Eq. (5) offers a slight improvement with a chi-square value of 84.2. Our analysis to fit the data of Fig. 4 assumes two circular loops. Because electroweak strings contain wiggles, they are unlikely to be perfectly circular. This would alter the expected average direction of polarization and could offer a better fit to the data, although determining the exact shape of the strings in question here may be a very difficult task.

Conclusion.—While searching for stable strings in the Universe today is a difficult endeavor, the potential to observe the imprint left over from an electroweak string

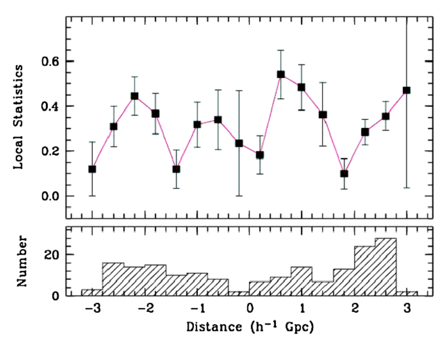

FIG. 3 (color online). A plot of the local statistics along the $A1$-$A3$ axis as described in Ref. [1]. The local statistics is a measure of the degree by which the quasar polarization vectors are preferentially aligned with other nearby quasars. A high local statistic value indicates a greater degree of alignment. Bins of size $\Delta r = 0.4h^{-1}$ Gpc are used. Instead of redshift, comoving distances of $r = 6[1 - (1+z)^{-1/2}]h^{-1}$ Gpc are used, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Objects in the direction of the NGP (SGP) are assigned positive (negative) distances. The histogram below the graph gives the number of quasars in each bin. This figure was taken directly from Ref. [1].

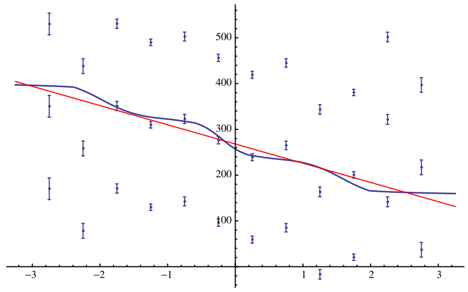

FIG. 4 (color online). Polarization angle vectorially averaged for 183 quasars along the $A1$-$A3$ axis from Ref. [1]. The objects are divided into bins of $\Delta z = 0.5$. Error bars show the 68% angular confidence interval [21]. The straight line is the best fit from Ref. [1] given by $\bar{\theta} = 268 - 42z$. The curvy line is our best fit described by Eq. (5). As in Fig. 13 from Ref. [1], each data point is replicated 3 times: at $\bar{\theta}$, $\bar{\theta} + 180$, and $\bar{\theta} + 360$.

remains an intriguing possibility. Linked strings may leave behind lines of magnetic flux imprinted in the Universe which could be stretched to cosmological scales both by expansion and by the fact that parallel lines of magnetic flux repel. Quasars that form in the vicinity of these magnetic fields are essentially forming in a background magnetic field. The quasars therefore preferentially form with their axes aligned parallel to the magnetic field. Another effect that synergistically works with this is the torque applied to a quasar host from an external magnetic field that tends to align the quasar axis with the background magnetic field. Other nearby quasars form in essentially the same average background field, thereby predicting the observed alignment of quasar polarization vectors. On large enough scales the effects of two looped magnetic fields would be observable as a rotation of the average direction of quasar polarization vectors.

The agreement between our theoretical model and observational data is very good. In particular, we are able to explain both the alignment of polarization vectors and the rotation of the polarization angle with the redshift, a feature which is not easily accommodated in simple *ad hoc* models. Our model gives clear predictions that can be tested once a greater sample size of quasar polarization data is available. We expect other quasar polarization angles along the $A1$-$A3$ axis to follow the pattern observed in Fig. 4. We may also look for quasar polarization angles away from the $A1$-$A3$ axis that still follow the pattern as predicted by Eq. (1). This observation will likely be more difficult, as it requires observing a large sample of objects through the galactic disk. We also expect that along the magnetic field lines shown in Fig. 1 the local statistics should indicate a significant degree of alignment, as long as the direction of the magnetic field is more or less perpendicular to our line of sight. (As the magnetic field becomes parallel to our line of sight, we expect the alignment effect to decrease.) Because our model predicts the Earth to lie near the center of these two strings, we expect a maximum degree of alignment along the $A1$-$A3$ axis, which is in agreement with the current data. Another interesting test of our model would be to look for the systematic effects such a magnetic field would have on CMB photons such as Faraday rotation. Because the current data cannot definitely tell that significant polarization vector alignments exist far from the $A1$-$A3$ axis, this is where the predictive power of our model lies. Future observations should be able to confirm or rule out our model of alignment.

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