# Evidence for a Nambu-Goldstone Boson

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Cosmic global strings dissipate their energy into Nambu-Goldstone bosons with a $1/k$ energy spectrum. These Nambu-Goldstone bosons can convert to photons in the magnetic fields of various astrophysical objects, in particular galactic halos, clusters of galaxies, and extended radio sources. Evidence that this does in fact occur is found in cosmic-ray and radio-astronomy data.

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Spontaneously broken global symmetries may occur in particle-physics models. If a global symmetry group $G$ breaks down to a subgroup $H$ by the appearance of a vacuum expectation value of magnitude $v$ and if the first homotopy group $\pi_1(G/H)$ is nontrivial, then the model will contain global strings. These objects are present in the Universe[1] today provided no inflation occurs after the phase transition at a temperature of order $v$ in which the $G \rightarrow H$ symmetry breaking occurs. Cosmic strings have received a lot of attention in recent years and their properties have been studied extensively.[2] However, the object usually studied is a gauge string. A gauge string has its energy localized in a thin tube and its dynamics is described by the Nambu-Goto action. On the other hand, the energy per unit length of a global string

$$\lambda \approx \pi v^2 \ln(vL) = \pi v^2 \int_{L^{-1}}^{v} \frac{dk}{k} \tag{1}$$

is spread all over space. In Eq. (1), $L$ is a long-distance cutoff. If $L$ is of order of the present horizon and $v$ is of order of the grand unification scale, then $\ln(vL) \approx 130$. The energy per unit length in the string core is of order $v^2$ and hence is only a fraction $1/\ln(vL)$ of the total $\lambda$. It cannot be assumed that the core behaves as a free gauge string obeying the Nambu-Goto action. Instead, the simplifying feature is the fact that most of the energy of a global string is in the *free* Nambu-Goldstone field outside the core.[3] In the limit $\ln(vL) \rightarrow \infty$, the process by which a bent global string straightens itself out is the free escape to infinity of the excess radiation in the Nambu-Goldstone field of a bent global string as compared with a straight one. The straightening out happens at the speed of light and at once and the energy spectrum of radiated Nambu-Goldstone bosons is $1/k$.[3] Indeed, because the energy spectrum of a free field is time independent, the energy spectrum of the radiated Nambu-Goldstone bosons is the difference between the energy spectra of the initial bent string and the final straight string, and both of these are $1/k$. (I am neglecting deviations from $1/k$ at wavelengths of order of the curvature radius of a bent string.) The cosmological energy density in radiated Nambu-Goldstone bosons at time $t$ since the big bang is[3] $\rho^{\rm NG}(t) \approx \pi v^2 \ln(vt)/t^2$. They have a $1/k$ spectrum extending over the range $t^{-1} \lesssim k \lesssim v$. In order that $\rho^{\rm NG}$ is less than the critical energy density for closure, one must have $v \lesssim 10^{17}$ GeV. Of course, it is likely that there are other more severe constraints on $v$, e.g., upper limits from the isotropy of the cosmic microwave background, lensing,[4] and the Gott-Kaiser-Stebbins effect,[5] as well as lower limits from astrophysical considerations.

Assuming that cosmic global strings exist, can one observe any manifestations of the radiated Nambu-Goldstone bosons? I will call these particles "omions" for short. I assume that the omion field $\varphi$ couples to the electromagnetic field through $\mathcal{L}_{\varphi\gamma\gamma} = +(\alpha/4\pi)\mathcal{N}(\varphi/v) \times F_{\mu\nu}\tilde{F}^{\mu\nu}$. We will see below that the required $\mathcal{N}$ is rather large, perhaps of order $10^5$. On the other hand, the coupling of the omion to two gluons must vanish, because otherwise the omion would be an axion and would acquire mass from nonperturbative QCD effects. Hence the omion is incompatible[6] with "simple" grand unification [i.e., the embedding of $\mathrm{SU}_L(2) \otimes \mathrm{U}_Y(1) \otimes \mathrm{SU}^c(3)$ into a *simple* gauge group such as SU(5)] because simple grand unification relates the two-photon coupling to the two-gluon coupling by a proportionality constant. On the other hand, the omion is consistent with everything known, including the standard model of the electroweak and strong interactions, to which an omion with the *effective* interaction $\mathcal{L}_{\varphi\gamma\gamma}$ can simply be added. The effective interaction $\mathcal{L}_{\varphi\gamma\gamma}$ may be generated by fermion triangle loops, or possibly by some other field-theory mechanism which we do not know about yet. An example of an omion model is the standard model plus a complex scalar field $\phi$ with a global $\mathrm{U}_0(1)$-symmetric self-interaction potential $V(\phi^\dagger\phi)$ such that $\phi$ takes on a very large expectation value $\langle\phi\rangle = v e^{i\varphi/v}$ (with $v$ of order $10^{14}$ GeV, for example), and $\mathcal{N}$ four-component fermions $L_i$ which acquire large masses through Yukawa couplings of the form $\mathcal{L}_Y = -\sum_{i=1}^{\mathcal{N}} K_i L_{iL} L_{iR} \phi + \mathrm{H.c.}$ The $L_i$ are neutral under $\mathrm{SU}_L(2) \otimes \mathrm{SU}^c(3)$ but all carry hypercharge 1. Some additional interactions among the $L_i$ may have to be postulated to assure their efficient annihilation in the very early Universe. In this model, the effective interaction $\mathcal{L}_{\varphi\gamma\gamma}$ is generated through heavy-fermion $L_i$ triangle loops. This and other omion models will be discussed in detail in a forthcoming paper.[7]

Like an axion, the omion can convert to a photon in a magnetic field.[8] Using the results of Ref. 8 and setting the axion mass to zero to go from the axion case to the omion case, one obtains for the $\varphi \leftrightarrow \gamma$ conversion probability in a homogeneous magnetic field

$$p_{\varphi\leftrightarrow\gamma}=\frac{1}{4}\left(\frac{\alpha}{\pi}\mathcal{N}\frac{1}{v}\right)^2 B^2L^2=1.32\times10^{-52}\left(\frac{BL\mathcal{N}}{1\text{ G cm}}\right)^2\left(\frac{10^{17}\text{ GeV}}{v}\right)^2, \tag{2}$$

where $B$ is the magnetic field transverse to the momentum $\mathbf{k}$ of the collinear omion and photon and $L$ is the length over which the magnetic field extends in the direction of $\mathbf{k}$. The photon produced is 100% polarized in the direction of $\mathbf{B}$. Equation (2) is valid only for a perfectly homogeneous magnetic field in otherwise empty space. In that case, the $\phi\leftrightarrow\gamma$ conversion is coherent. In the real world, however, coherence may be destroyed for a variety of reasons and one must then replace $L^2$ by $Ll$ in Eq. (2) where $l$ is the appropriate coherence length. In the situations of interest to us, coherence can be destroyed by lack of homogeneity of the magnetic field, the plasma frequency $\omega_{\text{pl}}$ which is an effective mass for the photon ($l=2k/\omega_{\text{pl}}^2$ for $k\gg\omega_{\text{pl}}$), and scattering of the photon off electrons and microwave background photons ($l$ is the corresponding scattering length). Note also that Eq. (2) assumes that $BL\mathcal{N}/v\ll10^9$ G cm/GeV. If $BL\mathcal{N}/v \gtrsim 10^9$ G cm/GeV, the omion-photon oscillation length is shorter than $L$ and $p_{\varphi\leftrightarrow\gamma}\sim1$.

By multiplying the flux of omions by the $\varphi\leftrightarrow\gamma$ conversion probability, one obtains the following differential $\gamma$-ray flux:

$$\frac{d\rho_{\varphi\leftrightarrow\gamma}}{D\Omega\, dk}\approx1.3\times10^{-50}\frac{\text{GeV}}{\text{cm}^2\text{ sec sr}}\frac{\mathcal{N}^2B^2Ll}{(1\text{ G cm})^2}\frac{1}{k}\left(\frac{H_0}{100\text{ km/sec Mpc}}\right)^2$$

$$\approx2.1\times10^{-39}\frac{\text{Jansky}}{\text{sr}}\frac{\mathcal{N}^2B^2Ll}{(1\text{ G cm})^2}\left(\frac{1\text{ GHz}}{k}\right)\left(\frac{H_0}{100\text{ km/sec Mpc}}\right)^2, \tag{3}$$

(where 1 Jansky $=10^{-26}$ W/m$^2$ Hz) in the case where there is a single object of negligible red shift in the line of sight. The right-hand side of Eq. (3) does not depend upon the scale of symmetry breaking $v$ because the $v^2$ in the omion flux cancels the $1/v^2$ in the $\varphi\leftrightarrow\gamma$ conversion probability. The only free parameter is $\mathcal{N}$. Below $\sim30$ MHz, radio waves from outer space are suppressed by the ionosphere and the solar wind. Above about $3\times10^6$ GeV, the flux of $\gamma$ rays is suppressed by $\gamma+\gamma_{3\text{K}}\to e^+ + e^-$, where $\gamma_{3\text{K}}$ is a microwave background photon. But between 100 MHz and $10^6$ GeV, $\varphi\to\gamma$ conversion predicts a flat photon spectrum on a logarithmic energy scale. One is most likely to observe this signal in the radio-wave (100 MHz-10 GHz) or the high-energy (1-$10^6$ GeV) parts of the electromagnetic spectrum because that is where the backgrounds from other astrophysical sources are lowest.

In the 100 MeV-$10^6$ GeV energy range, the observed diffuse $\gamma$-ray spectrum[9] is, in fact, approximately $1/k$:

$$\frac{d\rho^{\text{obs}}}{d\Omega\, dk}\approx(3\times10^{-7}\text{ GeV/cm}^2\text{ sec sr})\frac{1}{k}. \tag{4}$$

In Table I are listed those astrophysical objects most likely to be the dominant contributors to $\varphi\to\gamma$ conversion, i.e., the magnetic fields[10] associated with galactic halos, with clusters of galaxies, with the jets and lobes of extended radio structures and, finally, the hypothetical cosmological magnetic field. For the purpose of illustration, I have given *representative* values[10] for the magnet-

TABLE I. Representative values of the magnetic field, size, $\varphi\to\gamma$ conversion power, density, formation epoch, and contribution to the present diffuse electromagnetic background (for $10^8$ Hz $\lesssim k\lesssim10^6$ GeV) through $\varphi\to\gamma$ conversion.

| | $B$ (G) | $L$ (cm) | $(k/\mathcal{N}^2)dP_0/dk$ (erg/sec) | $n_0$ (cm$^{-3}$) | $z_f$ | $(k/\mathcal{N}^2)d\rho_{\varphi\leftrightarrow\gamma}/dk$ (erg/sec cm$^2$) |
|---|---|---|---|---|---|---|
| Galactic halos | $10^{-6}$ | $10^{23}$ | $2\times10^{27}$ | $10^{-75}$ | 15 | $2\times10^{-19}$ |
| Clusters of galaxies | $3\times10^{-8}$ | $10^{25}$ | $2\times10^{32}$ | $5\times10^{-78}$ | 3 | $4\times10^{-17}$ |
| Jets | $10^{-4}$ | width $2\times10^{22}(l)$ length $10^{23}$ | $2\times10^{29}$ | $10^{-78}$ | 15 | $2\times10^{-20}$ |
| Lobes | $10^{-6}$ | $2\times10^{23}$ | $2\times10^{28}$ | $10^{-78}$ | 15 | $2\times10^{-21}$ |
| Cosmological magnetic field | $<10^{-9}$ | $10^{28}$ | $<2\times10^{41}$ | $10^{-84}$ | | $<10^{-15}$ |

ic-field strengths and sizes of these objects. I have not attempted to express either the intrinsic variability or the uncertainty in our knowledge of these quantities. For the objects of Table I, $l$ is of order $L$ and this has been used to estimate their $\varphi \to \gamma$ conversion luminosites (column 3). The estimates of $d\rho_{\varphi \to \gamma}/dk$ in column 6 take account of the fact that the process of $\varphi \to \gamma$ conversion has been going on for some time. $z_f$ is the red shift at formation time used in the estimate. If one assumes that the high-energy cosmic $\gamma$ rays are due to $\varphi \to \gamma$ conversion, then one concludes from Table I that $\mathcal{N}$ is in the range $10^3$ to $3\times10^5$ depending on which type of conversion site is most important. In addition, the $1/k$ spectrum of Eq. (3) must extend all the way down to about $10^8$ Hz. As a signal, this is far below the average electromagnetic background in all energy bands except the radio range ($10^8$–$10^{10}$ Hz). Hence, I turn to radio astronomy for evidence for or against the omion origin of high-energy cosmic $\gamma$ rays.

Polarization maps have been made of many extended radio sources. The following trend has been noted.[11] The direction of the polarization is perpendicular to the jet axis in sources whose total radio luminosity $P_{\rm tot}^{1.4}$ at 1.4 GHz is large compared with $P_{\rm crit}^{1.4} \equiv 10^{24.5}$ W/Hz, whereas in sources with $P_{\rm tot}^{1.4} \lesssim P_{\rm crit}^{1.4}$ the polarization changes from perpendicular to the jet axis near the core of the source to parallel to the jet axis some distance away from the core. Up until now, it has been taken for granted that the source of nonthermal radio-wave emission from astrophysical objects is synchrotron radiation and synchrotron radiation is polarized perpendicular to the magnetic field. The natural direction for the magnetic field is parallel to the jet axis. To explain the *systematic* change of the direction of the polarization from perpendicular to the jet axis near the core to parallel to the jet axis some distance away from the core is rather difficult in terms of synchrotron radiation alone,[12] although three-dimensional **B**-field configurations have been put forth which do the job.

On the other hand, the qualitative features of the polarization maps are those one would expect from a combination of synchrotron emission and $\varphi \to \gamma$ conversion. Recall that $\varphi \to \gamma$ conversion radiation is polarized parallel to the magnetic field and note that the core of the radio source is the obvious provider of a large part of the kinetic energy that the electrons dissipate in synchrotron radiation. Away from the core, the electrons become depleted in energy and $\varphi \to \gamma$ conversion starts to dominate over synchrotron emission. Hence the change in the direction of polarization. This interpretation is corroborated by other features of the radio maps. The spectral index $\alpha$ (defined by $dP/dk \sim k^{-\alpha}$) is 1 for $\varphi \to \gamma$ conversion. For synchrotron emission, $\alpha$ depends upon the energy distribution of the electrons. Typically, $\alpha \approx 0.5$ to 0.6 near the core. But $\alpha$ increases, often approaching a value near 1, away from the core.[11] More generally, in those cases where detailed information on both the polarization and the spectral index is available, there is a significant correlation between those regions which have high spectral index and those where the polarization is parallel to the jet axis.[13,14] When polarization maps of the same object at two different frequencies are available, the polarization at the lower frequency is parallel to the jet over wider regions of the map than at the higher frequency.[14] In other words, there are regions where the polarization is perpendicular to the jet axis at high frequency but parallel to the jet axis at low frequency. This is very hard to understand in terms of synchrotron radiation alone because synchrotron radiation is perpendicular to the magnetic field at all frequencies. It is also very difficult to attribute this phenomenon to Faraday rotation. On the other hand, one does expect this to occur, if both synchrotron radiation and $\varphi \to \gamma$ conversion are present. Indeed, in those regions where the two are nearly equal in power, $\varphi \to \gamma$ conversion dominates over synchrotron radiation at low frequency because it has the steeper spectrum.

What is the value of $\mathcal{N}$ implied by the evidence for $\varphi \to \gamma$ conversion in the magnetic fields of extended radio sources? The value of $P_{\rm crit}^{1.4}$ can be used to obtain an estimate. An extended radio source begins to exhibit the features associated with $\varphi \to \gamma$ conversion when the $\varphi \to \gamma$ luminosity of its jets and lobes equals a certain fraction of its total luminosity. I roughly estimate this fraction to be $\frac{1}{3}$ because $\varphi \to \gamma$ conversion produces a higher degree of polarization than does synchrotron radiation. If one sets the luminosity of the representative extended radio source of Table I equal to $\frac{1}{3} P_{\rm crit}^{1.4}$, one obtains $\mathcal{N} \approx 2\times10^5$, in remarkable agreement with the range of values obtained earlier from high-energy cosmic $\gamma$ rays. I have compared the local values of the surface brightness of several extended radio sources with the local values of the magnetic field estimated using the equipartition hypothesis. The resulting estimates of $\mathcal{N}$ were in the range $\frac{1}{2}\times10^5$ to $2\times10^6$. It should be emphasized that equipartition provides only a rough estimate of the magnetic field. In particular, by changing the assumed ratio of proton to electron kinetic energy in the synchrotron emitting plasma, one can increase the estimates of the magnetic fields by up to a factor $\sim 9$. This would decrease by a factor of 9 the range of $\mathcal{N}$ estimates given above, bringing it in perhaps closer agreement with the range of $\mathcal{N}$ estimates from cosmic $\gamma$ rays.

I conclude from the evidence presented here that omions exist. Equation (3) has many detailed predictions which allow further comparison with observation. To give just one example, in those places on the radio maps where there is a change of about 90° in the direction of polarization between 1.4 and 4.9 GHz, there must be an extinction of the degree of polarization and an abrupt change in the direction of polarization at an intermediate frequency, whereas Faraday rotation predicts a smooth change in the direction of polarization. It should be straightforward to rule out or confirm the omion. Finally, there are several other phenomenologies which have remained puzzling for many years and which, for rather obvious reasons, may be related to omion physics. The list of those which I plan to investigate in the near future includes ultrahigh-energy nucleon cosmic rays, the x-ray emission from extended radio sources, the luminosity of quasars, and $1/f$ noise.

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