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ENERGETIC AND RADIATIVE CONSTRAINTS ON HIGHLY RELATIVISTIC JETS

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ABSTRACT

We examine constraints on the energetics and radiative efficiencies of highly relativistic, synchrotron-emitting jets. If the observed intraday radio variability of compact radio sources is intrinsic and results from incoherent synchrotron radiation, then the associated jets must have bulk Lorentz factors in the range $\Gamma \sim 30$–100, several times larger than the largest values inferred from superluminal expansion, and larger even than the values required to avoid the synchrotron self-Compton catastrophe. We show that such highly relativistic jets produce synchrotron radiation with extremely low radiative efficiency. As a result they must carry enormous kinetic energy fluxes, $L_j \gtrsim 10^{47}(\Delta\Omega/0.1 \text{ sr})$, where $\Delta\Omega$ is the solid angle subtended by the jet, in order to produce "apparent" synchrotron brightness temperatures $\gtrsim 10^{16}$ K. Energy losses by such jets should be strongly dominated by Compton scattering of diffuse ambient radiation, and they should produce large X-ray and gamma-ray fluxes.

Subject headings: galaxies: jets — gamma rays: theory — radiation mechanisms: nonthermal — radio continuum: galaxies

1. INTRODUCTION

It has been evident for several years that compact radio jets possess bulk flows with Lorentz factors Γ as large as 10. Until recently, the strongest evidence has come directly from VLBI observations of superluminal motion, although other pieces of evidence such as one-sidedness, brightness temperature limits on variable sources, and comparison of predicted and observed X-ray flux densities have indirectly supported this view.

There are now additional, independent indications of highly relativistic outflow. Some blazars have been detected as strong gamma-ray sources which vary on timescales as short as days (Hartman et al. 1992; Lin et al. 1992). If the source were actually as small as a few light days, then no gamma rays would escape (irrespective of the emission mechanism) because the photon density (due to the jet radiation itself or diffuse ambient radiation surrounding the jet) would be so high that pair production would occur. This process can be avoided by highly relativistic outflow with $\Gamma \gtrsim 10$, which allows a larger source size and raises the energy threshold for pair production in the observer's frame (Sikora, Begelman, & Rees 1994, hereafter SBR). Moreover, relativistic Doppler beaming lowers the luminosity requirements from inferred values $\sim 10^{48}$ ergs s^{-1} (for an isotropic source) to more reasonable values.

Intraday radio variability (IDV) of some compact radio sources may also be an indicator of highly relativistic bulk flow in jets. Radio variability within a single day, with up to 30% amplitude, appears to occur in at least a quarter of all compact extragalactic sources (Krichbaum, Quirrenbach, & Witzel 1992; Witzel 1992). If the source dimensions were limited to $c\,\Delta t$, these rapid variations would imply "apparent" brightness temperatures vastly higher than are compatible with an incoherent synchrotron source. In the case of 0917+624 (Quirrenbach et al. 1989; Qian et al. 1991), the "apparent" brightness temperature is $T_{\rm app} \gtrsim 10^{17}$ K, more than five orders of magnitude higher than the Compton catastrophe limit. If the observed variations, with timescale Δt, are produced by time-varying inhomogeneities in a relativistic jet, the maximum proper size of the emitting region in *any* dimension is limited to $c\,\Delta t\Gamma$ (Marscher & Gear 1985), unless its geometry, its orientation with respect to the observer, and the propagation of the variability signal are all highly contrived. Given the common occurrence of IDV, such fine tuning is very implausible. The brightness temperature, in a frame comoving with the jet material, is reduced below its apparent value by at most a factor $\sim\Gamma^3$, rather than the factor $\sim\Gamma^5$ claimed by Qian et al. (1991). Thus, it seems hard to escape the conclusion that the bulk flows exhibiting IDV have Lorentz factors $\gtrsim 100$, if the emission is due to incoherent synchrotron radiation.

It is still not certain that IDV arises from intrinsic fluctuations in the source. The most likely *extrinsic* cause of IDV, interstellar scintillation, should reveal itself through its strong frequency dependence. In particular, it could be ruled out if fluctuations at optical wavelengths do prove to be strongly correlated with those in the radio, as has been suggested for the object 0716+714 (Quirrenbach et al. 1991). Alternatively, coherent plasma oscillations might produce radiation that mimics synchrotron emission, but with much higher brightness temperatures (Benford 1992); however, effects due to Compton scattering (especially stimulated Compton scattering) may prevent radiation produced in this way from escaping (Coppi, Blandford, & Rees 1993 and references therein).

In this *Letter* we consider the hypothesis that the rapidly variable radio emission is indeed incoherent synchrotron emission, and discuss some of the constraints imposed by such high Lorentz factors on the energetics and radiative properties of the jet. Our discussion is couched in terms of the intraday-variable sources, but the conclusions apply as well to highly relativistic jets producing steady fluxes of synchrotron radiation.

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2. SYNCHROTRON CONSTRAINTS ON JET ENERGETICS

We assume that the observed emission is dominated by the material whose velocity makes an angle $\sim\Gamma^{-1}$ with respect to the line of sight; hence we set the Doppler factor $\mathscr{D} \sim \Gamma \equiv 100\Gamma_{100}$. Physical limitations on the apparent variability of relativistic jets, taking into account the distinction between the pattern speed of the variability "disturbance" and the bulk speed of the plasma, can be captured in a simple three-parameter model which we derive elsewhere (SBR). Following the notation of SBR, we take the parameters to be (1) β'_p, the speed with which the pattern of the disturbance propagates in the frame comoving with the fluid; (2) $\Delta t'$, the characteristic timescale of the radiation "event," also measured in the comoving frame; and (3) η, the fraction (≤ 1) of the time $\Delta t'$ during which each fluid element "triggered" by the disturbance is assumed to radiate. (Here, as elsewhere in this *Letter*, primed quantities denote measurements made in the fluid frame.) We define

$$f_p \equiv \frac{\beta_p}{\Gamma^2(1-\beta_p \cos\theta_{\rm obs})} \approx 2\left(1+\frac{\Gamma^2}{\Gamma_p^2}\right)^{-1} \leq 2\,, \qquad (1)$$

where β_p is the pattern speed as measured in a local, stationary "observer's" frame, and $\Gamma_p \equiv (1-\beta_p^2)^{-1/2}$ is assumed to be $\gg 1$. Then the *observed* timescale of variability is given by

$$\Delta t \sim \frac{\Delta t'}{\Gamma}\frac{\eta + f_p}{f_p} \equiv \frac{\Delta t'}{\Gamma}\phi_p\,, \qquad (2)$$

and the radiation energy density in the comoving frame must generally satisfy

$$u'_{\nu'} \approx \frac{(1+z)\Delta S_\nu d_L^2}{c^3(\Delta t)^2\Gamma^5}\frac{\phi_p^3}{\eta^2\beta_p'^2}\,, \qquad (3)$$

where ν is the observing frequency, ΔS_ν is the observed change in flux during time Δt, and z and d_L^2 are respectively the redshift and luminosity distance of the source. To derive equation (3) (and eq. [5] below), we have assumed that the radiating zone has a dimension (in the comoving frame) $\sim c\,\Delta t\Gamma\eta\,|\beta'_p|/\phi_p$ (SBR). Using equation (3), one can then define an "apparent" brightness temperature $T_{\rm app}$ and relate it to the actual brightness temperature in the comoving frame through the expression

$$T'_b \approx \frac{c^3 u'_{\nu'}}{8\pi\nu'^2 k} \approx \Gamma^{-3} T_{\rm app}\frac{\phi_p^3}{\eta^2\beta_p'^2}\,. \qquad (4)$$

Note that $(\phi_p^3/\eta^2\beta_p'^2) \geq 1$, implying that $T'_b \gtrsim \Gamma^{-3}T_{\rm app}$. The "typical" variations of 0917+624 described by Qian et al. (1991)—$\Delta S_\nu = 0.2$ Jy, $\Delta t = 1$ day at $\nu = 5$ GHz—yield (for $H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$) $T_{\rm app} \gtrsim 2 \times 10^{17}$ K. Most other intraday-variable sources measured to date appear to be less extreme, with lower limits to the apparent brightness temperatures of order 10^{16} K or less.

The energy density in relativistic electrons required to produce the observed variable synchrotron emission is given by

$$\varepsilon'_{\rm rel} \approx 6.1 \times 10^{-11}\nu_5^{5/2}B'^{-3/2}T'_{b,11}\Gamma_{100}^{-7/2}\ln\left(\frac{\gamma_{\rm max}}{\gamma_{\rm min}}\right) \times \left(\frac{\Delta t}{1\ {\rm day}}\right)^{-1}\frac{\phi_p}{\eta\,|\beta'_p|}\ {\rm ergs\ cm^{-3}}\,, \qquad (5)$$

where $5\nu_5$ GHz is the observing frequency (at the redshift of the source), $T'_{b,11} \equiv T'_b/(10^{11}$ K) is parameterized in terms of a characteristic brightness temperature associated with synchrotron self-absorption (see eq. [7] below), and we have assumed an isotropic power-law electron energy distribution $n(\gamma) \propto \gamma^{-2}$ in the plasma frame for electron Lorentz factors between $\gamma_{\rm min}$ and $\gamma_{\rm max}$ (Rybicki & Lightman 1979). Note that the results obtained below are not sensitive to the electron energy distribution, if the optically thin synchrotron spectral index lies in the usual range $0.5 \lesssim \alpha \lesssim 1$; the above electron energy distribution assumes $\alpha = 0.5$. Synchrotron self-absorption imposes an upper limit on the magnetic field strength in the emitting region,

$$B' < 2.6 \times 10^{-3}\nu_5\Gamma_{100}^{-1}(T'_{b,11})^{-2}\ {\rm G}\,, \qquad (6)$$

which, combined with equation (5), allows us to constrain T'_b in terms of the ratio of $\varepsilon'_{\rm rel}$ to the magnetic energy density, $\varepsilon'_B = B'^2/8\pi$:

$$T'_b < T'_{\rm abs} \equiv 9.5 \times 10^{10}\left[\frac{\varepsilon'_{\rm rel}}{\varepsilon'_B}\frac{\nu_5(\Delta t/1\ {\rm day})}{\ln(\gamma_{\rm max}/\gamma_{\rm min})}\frac{\eta\,|\beta'_p|}{\phi_p}\right]^{1/8}\ {\rm K}\,. \qquad (7)$$

This constraint is extremely insensitive to both the electron energy distribution and the ratio of $\varepsilon'_{\rm rel}$ to ε'_B, and shows that T'_b must fall well below the Compton catastrophe limit of $\sim 10^{12}$ K (Kellermann & Pauliny-Toth 1969) unless $\varepsilon'_{\rm rel}/\varepsilon'_B \gg 1$ by several orders of magnitude. Even if the latter condition applied, an intrinsic brightness temperature close to the Compton catastrophe limit would imply a jet power greatly exceeding the severe lower bound of equation (9). We therefore regard $\approx 10^{11}$ K as an upper limit to plausible values of T'_b. Readhead (1994) draws a similar conclusion and, by analyzing data from powerful extragalactic radio sources, concludes that the sources are not far from equipartition between magnetic and relativistic particle energy, $\varepsilon'_{\rm rel}/\varepsilon'_B \sim 1$. From equation (7) we obtain a lower limit on the bulk Lorentz factor of a variable source with *apparent* brightness temperature of $10^{17}T_{\rm app,17}$ K, $\Gamma \gtrsim 100T_{\rm app,17}^{1/3}$. Thus, the bulk Lorentz factors of jets exhibiting intraday variability would have to be *even higher* than the values needed to avoid the Compton catastrophe, and $\gtrsim 10$ times larger than typical values indicated by superluminal motion and apparent brightness temperatures.

The overall energetic requirements for producing the variable synchrotron emission are quite severe. To see this, first note that the minimum *total* energy density of magnetic field plus relativistic electrons occurs when $\varepsilon'_{\rm rel} \approx (4/3)\varepsilon'_B$. From equation (5), we obtain

$$\varepsilon'_{\rm tot} > 7.3 \times 10^{-7}\nu_5^{10/7}\Gamma_{100}^{-2}(T'_{b,11})^{4/7}\left[\ln\left(\frac{\gamma_{\rm max}}{\gamma_{\rm min}}\right)\right]^{4/7} \times \left(\frac{\Delta t}{1\ {\rm day}}\right)^{-4/7}\left(\frac{\phi_p}{\eta\,|\beta'_p|}\right)^{4/7}\ {\rm ergs\ cm^{-3}}\,. \qquad (8)$$

The energy flux then satisfies $L_j \geq \Gamma^2\varepsilon'_{\rm tot}cr^2\,\Delta\Omega$, where r is the distance of the emitting region from the source of the jet and $\Delta\Omega$ is the solid angle subtended by the jet. While we have assumed that the emitting region sampled by an observer subtends an angle $\theta \sim \Gamma^{-1}$ around the line of sight, the jets themselves are presumably much wider than this, probably subtending solid angles as large as ~ 0.1 sr (Phinney 1985). Otherwise it would be difficult to understand the number of compact radio sources exhibiting intraday variability and other manifestations of highly relativistic flow (Krichbaum et al. 1992). The distance r must exceed the distance traveled by the emitting region during the episode of variability, implying $r > c\,\Delta t \Gamma^2 f_p$ (SBR). At fixed T'_b and $T_{\rm app}$, the lower limit on the energy flux is itself minimized for $\eta = (7/9) f_p = \beta'_p = 1$, from which we obtain $r > 38(\Delta t/1\ {\rm day})(T_{{\rm app},17}/T'_{b,11})^{2/3}$ pc and

$$L_j > 3 \times 10^{47} \nu_5^{10/7} T_{{\rm app},17}^{4/3} (T'_{b,11})^{-16/21} \left[\ln\left(\frac{\gamma_{\rm max}}{\gamma_{\rm min}}\right)\right]^{4/7} \times \left(\frac{\Delta t}{1\ {\rm day}}\right)^{10/7} \left(\frac{\Delta\Omega}{0.1\ {\rm sr}}\right) {\rm ergs\ s^{-1}}\ . \qquad (9)$$

Since $T'_b \leq T'_{\rm abs} \sim 10^{11}$ K, we see that the power requirements are lowest when the source has the maximum permitted intrinsic brightness temperature, i.e., when the synchrotron emission is marginally self-absorbed. Although it would seem that this rather severe power requirement could be ameliorated if the episodes of variability actually comprised a superposition of much shorter variability events [since $L_{\rm min} \propto (\Delta t)^{10/7}$, apparently], this is not the case, since we have derived equation (9) under the assumption that $T_{\rm app} \propto (\Delta t)^{-2}$ (with other parameters held constant; see eqs. [3] and [4] and accompanying discussion). Therefore, for a source with fixed flux variations at a given frequency, equation (9) predicts that shorter timescale variations imply more power, not less.

Thus, we find that a relativistic jet exhibiting intraday radio variability must be a very inefficient emitter of synchrotron radiation. This is basically because, for a given jet power L_j, both the particle energy density and the magnetic field in the comoving frame become very low when Γ is large. Even under the most optimistic circumstances, a jet of opening angle 0.1 sr and an apparent brightness temperature $\gtrsim 10^{16}$ K would require a power comparable to the total power inferred for a luminous quasar in order to produce the observed variable emission. Yet many of the sources exhibiting intraday variability are rather ordinary BL Lac objects (Witzel 1992) which are thought to belong to a low-luminosity class of active galaxies responsible for F-R I radio sources. The constraint would be eased somewhat if the power at any one time were concentrated in a smaller solid angle than 0.1 sr; the frequency with which sources appear to exhibit intraday variability could then reflect fluctuations in the jet direction over a much wider solid angle. However, it is difficult to escape the conclusion that only a small subset of IDV sources could exhibit apparent brightness temperatures in excess of 10^{15}–10^{16} K, if this phenomenon were indeed the result of synchrotron emission.

3. COMPTON SCATTERING

Any diffuse ambient radiation field will be strongly Doppler-boosted in the comoving frame of a highly relativistic jet. If the energy density in the comoving frame exceeds that of the local magnetic field, ε'_B, then Compton losses will dominate over synchrotron emission. Such an interaction has been proposed to account for the high-energy gamma rays observed from many blazars by the EGRET instrument on the *Compton Gamma Ray Observatory* (Dermer & Schlickeiser 1993; SBR; Blandford 1993). In this section we examine the conditions under which Compton losses would dominate the emission from relativistic jets. Under extreme conditions, these losses could "quench" the synchrotron variability by cooling the electrons needed to produce the synchrotron emission in a time much shorter than $\eta\,\Delta t'$.

Relativistic Doppler boosting favors the Comptonization of external radiation over synchrotron self-Compton (SSC) emission. Indeed, we have shown that the comoving brightness temperature of the synchrotron radiation falls well below the Compton catastrophe threshold of $\sim 10^{12}$ K, implying that SSC emission is negligible. The energy density of the diffuse radiation field likely to be present in the synchrotron-emitting region is highly uncertain. There are at least three sources of such radiation: the cosmic microwave background radiation, starlight, and a portion of the radiation from the nucleus which has been scattered or otherwise reprocessed by dust, free electrons, or interstellar and circumnuclear clouds. The latter probably dominates the diffuse radiation energy density at $r \lesssim 10$ pc, with

$$u_{\rm diff,sc} \sim \frac{\tau L_{\rm nuc}}{4\pi r^2 c} = 3 \times 10^{-7} L_{46} \left(\frac{\tau}{0.01}\right) \left(\frac{r}{10\ {\rm pc}}\right)^{-2} {\rm ergs\ cm^{-3}}\ , \qquad (10)$$

where $L_{\rm nuc} = 10^{46} L_{46}$ ergs s^{-1} is the luminosity of the nucleus and τ is the fraction reprocessed at radii $\sim r$.

As measured in the comoving frame, this energy density is amplified by a factor $\sim \Gamma^2$ and easily dominates over the magnetic energy density, which is constrained by equation (6) to satisfy $\varepsilon'_B \equiv B'^2/8\pi < 2.7 \times 10^{-7} \nu_5^2 \Gamma_{100}^{-2} (T'_{b,11})^{-4}$ ergs cm^{-3}. Since the ratio of Compton to synchrotron emission is $u'_{\rm diff}/\varepsilon'_B$, the Compton luminosity should be much higher than the synchrotron luminosity, even if the fraction of the nuclear luminosity reprocessed in the vicinity of the jet is very small. X-ray and gamma-ray observations can eventually be used to set upper limits to the radiative efficiencies of relativistic plasma emission in the regions responsible for the IDV radio flux. (Note that the portions of jets responsible for strong variable gamma-ray emission from blazars [see SBR] probably have values of r and Γ too small to contribute much to the radio fluxes from these objects.)

4. DISCUSSION

We have analyzed the implications of intraday radio variability of blazars, under the assumption that the variable emission is incoherent synchrotron radiation from a relativistic jet. Obtaining the observed flux variations and variability timescales requires bulk Lorentz factors in the range of 30–100, i.e., considerably higher than the values hitherto inferred from superluminal motion. The synchrotron radiative efficiency of such a highly relativistic jet would be extremely small, implying that the jet would have to carry large fluxes of electromagnetic and kinetic energy in order to produce the observed radio emission. This inefficiency places an upper limit on the bulk Lorentz factor of a bright synchrotron-emitting jet, and also limits the "apparent" brightness temperature attainable by an intraday-variable source to values not much above those already observed. Energetic and observational limits on Compton losses to ambient diffuse radiation (which must occur at some level) may constrain the maximum Lorentz factors of synchrotron-emitting jets still further. These constraints are illustrated in Figure 1.

It is extremely unlikely that such high bulk Lorentz factors can be attained through any radiative or thermal acceleration process (Phinney 1987), but there is no theoretical reason why such speeds could not be obtained from hydromagnetic acceleration mechanisms (Begelman 1994). Hydromagnetic acceler-

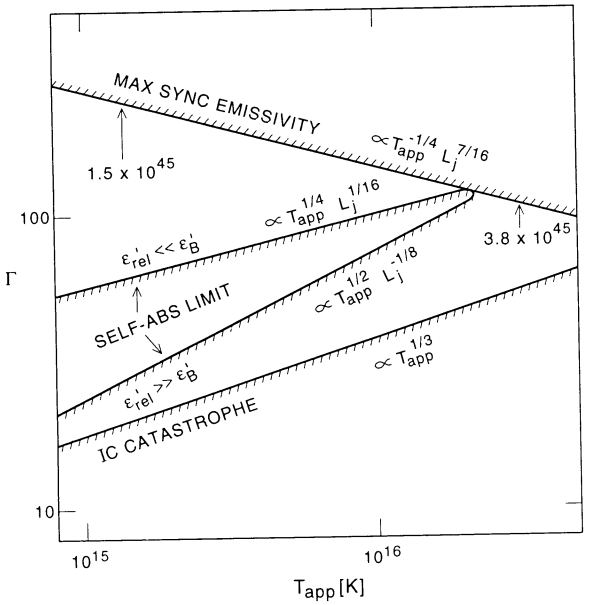

FIG. 1.—Constraints on the bulk Lorentz factor Γ required to produce a given apparent brightness temperature T_{app} (eq [4]) at 5 GHz, as inferred from variability with $\Delta t = 1$ day. Forbidden parameter regimes are indicated by hatching. Curves are shown for fixed jet power $L_j = 10^{47}$ ergs s^{-1} and $\Delta\Omega = 0.1$ sr, but scaling with L_j is indicated. Synchrotron self-absorption provides a more stringent lower limit on Γ than the inverse Compton (IC) catastrophe, while the maximum synchrotron emissivity provides an upper limit. The maximum T_{app} occurs at the apex of the allowed triangle, where $\varepsilon'_{rel} \approx \varepsilon'_B$. The jet also emits X-rays and gamma rays by inverse Compton scattering of ambient radiation. The numbers marked by arrows on the maximum emissivity curve are observed Compton luminosities produced by the radio-emitting electrons, assuming $L_{nuc} = 10^{46}$ ergs s^{-1} and $\tau = (10^{15}\ \mathrm{cm}/r)^{0.5}$ in eq. (10), with r determined from Γ and Δt as described in text.

ation naturally produces flows in which the kinetic energy flux and Poynting flux are of comparable magnitude (Blandford & Payne 1982; Li, Chiueh, & Begelman 1992b; Begelman & Li 1994; Tomimatsu 1994). Strong shocks in such flows, with efficient particle acceleration, would therefore produce a rough equipartition between magnetic and particle energies. To avoid excessive Compton losses near the central engine, the acceleration must be gradual, and the acceleration zone must extend over several decades in radius. It seems that hydromagnetic acceleration can produce such behavior (Li, Begelman, & Chiueh 1992a). The jets probably subtend solid angles ΔΩ of order 0.1 sr, to account for the number of compact radio sources exhibiting intraday variability and other manifestations of relativistic flow (Krichbaum et al. 1992). Again, this assumption is consistent with hydromagnetic acceleration models, which predict very gradual collimation of the flow under plausible circumstances (Chiueh, Li, & Begelman 1991; Begelman & Li 1994).

We expect the variable emission at a given frequency to come predominantly from the region of the jet which is marginally opaque to synchrotron self-absorption. This conjecture could be tested, in principle, by measuring the spectral index and polarization of the variable emission. If the emission were marginally self-absorbed, we would expect to observe a flatter spectrum than that usually associated with optically thin synchrotron emission, and also to see variations in the spectral index inversely correlated with the fluctuating intensity of the source. Fluctuations in the optical depth of the source should also be accompanied by 90° flips in the position angle of polarization, an effect which may have been detected in 0917+624 (Quirrenbach et al. 1989).

In summary, the presently claimed IDV data appear to be marginally consistent with the incoherent synchrotron hypothesis. This reduces the motivation for invoking coherent processes (e.g., Benford 1992; Lesch 1992). However, the most extreme levels of variability claimed to date fall right at the limit: any radio variations that were substantially more rapid could not be accommodated readily without invoking radiation processes that permit higher intrinsic brightness temperatures.

Note that our arguments set an upper limit to the Lorentz factor specifically for a jet (or a part of a jet) that emits synchrotron radiation above some threshold flux level. They do not rule out far higher values in jets that are simply conduits for energy, or which emit via inverse Compton scattering of ambient radiation. It is quite possible that particle kinetic energy and Poynting flux can be carried by very high Γ jets, with the observed synchrotron radiation coming from a violently sheared boundary layer that moves more slowly (though perhaps still relativistically). The M87 jet may be an instance of this (Begelman 1993; Begelman & Rees 1994).

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