SPACe VLBI Observations Show $T_b > 10^{12}$ K in the Quasar NRAO 530

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Abstract

We present here space-based VLBI observations with VLBI Space Observatory Program (VSOP) and a southern hemisphere ground array of the gamma-ray blazar NRAO 530 at 1.6 and 5 GHz. The brightness temperature of the core at 1.6 GHz is $5 \times 10^{11}$ K. The size is near the minimum observable value in the direction of NRAO 530 due to interstellar scattering. The 5 GHz data show a single component with a brightness temperature of $\sim 3 \times 10^{12}$ K, significantly in excess of the inverse Compton limit and of the equipartition brightness temperature limit. This is strong evidence for relativistic motion in a jet requiring model-dependent Doppler boosting factors in the range 6–60. We show that a simple homogeneous sphere probably does not model the emission region accurately. We favor instead an inhomogeneous jet model with a Doppler boosting factor of 15.

Subject headings: galaxies: active — galaxies: jets — radiation mechanisms: nonthermal — techniques: interferometric

1. Introduction

Compact extragalactic radio sources typically exhibit brightness temperatures in the range of $10^{10}$–$10^{11}$ K (Kellermann et al. 1998). These brightness temperatures are near the limit of what can be measured by ground-based very long baseline interferometry (VLBI) and are near the limits imposed by intrinsic physical processes (Readhead 1994). Historically, the brightness temperature limit has been attributed to the inverse Compton (IC) catastrophe, a process in which the high-energy electrons that produce the radio synchrotron photons are rapidly cooled by scattering the same photons to higher energies (e.g., Kellermann & Pauliny-Toth 1969). This process is considered to be a likely source for the high-energy gamma rays that are identified with very compact radio sources (von Montigny et al. 1995). Brightness temperatures in excess of the IC limit have been interpreted as the effect of Doppler boosting in a relativistic jet beamed toward the observer with a Doppler boosting factor $\delta \sim 10$.

Readhead (1994) has shown that the actual distribution of interferometrically measured brightness temperatures does not correspond to the distribution expected by a sample limited by IC scattering. Instead, the distribution indicates that brightness temperatures are governed by an unspecified mechanism that maintains equipartition of energy between magnetic fields and particles in a synchrotron-emitting region. This sets a brightness temperature limit that is $\sim 3$–10 times lower than the IC limit. Brightness temperatures in excess of this limit are again due to Doppler boosting.

Ground-based VLBI measurements of brightness temperatures have a limit of $\sim 5.6 \times 10^{10}(1 + z) S$ K, where $S$ is the flux density in Janskys and $z$ is the cosmological redshift. With techniques of superresolution, lower limits to brightness temperatures have been inferred that are greater than $10^{12}$ K (e.g., Moellenbrock et al. 1996). VLBI observations with an orbiting antenna permit the detection of fully resolved components with brightness temperatures greater than $10^{12}$ K (Linfield et al. 1989). Observations with the VLBI Space Observatory Program (VSOP) have baselines greater than two Earth diameters, quadrupling the maximum detectable brightness temperature (Hirabayashi 1998).

We present here observations with VSOP of the blazar NRAO 530 at 1.6 and 5 GHz. NRAO 530 (J1733–1304) recently underwent a bright millimeter and radio wavelength flare that appears to be correlated with the creation of a new component in the jet and with an increase in gamma-ray activity (Bower et al. 1997). NRAO 530 is a $m_\gamma \approx 18.5$ mag QSO (Welch & Spinrad 1973) with a redshift $z = 0.902$ (Junkkarinen 1984). It is a gamma-ray active blazar with a bolometric luminosity of $0.9 \times 10^{50} h^{-2}$ ergs s$^{-1}$, assuming isotropic emission (Nolan et al. 1996). Throughout this Letter we assume $q_0 = 0.5, H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$, and $h = 0.7$, which implies an angular-to-linear scale conversion of 6.0 pc mas$^{-1}$ and a luminosity distance of 4.4 Gpc.

In § 2, we present the observations and data reduction. In § 3, we discuss the implications of the high brightness temperature that we detect in NRAO 530.

2. Observations and Data Reduction

2.1. Observations, Correlation, and Fringe Fitting

NRAO 530 was observed by VSOP and an array of ground radio telescopes on 1997 September 8 and 9. Observations in left-circular polarization at 1.6 and 5 GHz were done in two separate 5 hr orbits of the Highly Advanced Laboratory for Communications and Astronomy (HALCA), the VSOP satellite. The Usuda tracking station was used during the observations. System temperatures were measured during adjacent tracking passes. The ground radio telescopes (GRTs) consisted of Usuda (Japan), Seshan (China), Mopra (Australia), and Australia Telescope (AT). The ground-based observations were approximately 8 hr in duration. Figure 1 displays the $u$–$v$ coverage for the 5 GHz experiment.

The data were recorded in the S2 format with two intermediate-frequency bands, each with a bandwidth of 16 MHz. Data were correlated in 1998 March at Penticton (Carlson et al. 1998). The space-ground and ground-ground baselines were accumulated with periods of 0.1 and 2 s, respectively. The data
were binned in 128 and 256 frequency channels at 1.6 and 5 GHz, respectively.

Initial steps in data reduction were performed with the 1998 April 15 version of AIPS. Fringe fitting was done in two steps. In the first step, single-band delays and rates were determined for the GRTs alone. In the second step, the previous GRT solutions were applied and new single-band delay and rate solutions for VSOP alone were found. Fringe fitting simultaneously GRTs with VSOP produced bad solutions that did not correctly eliminate all single-band delays.

Strong fringes from VSOP to Usuda were consistently detected. Solution intervals of 60 s were employed at both frequencies. At 1.6 GHz, fringe amplitudes to VSOP were 0.1–1 Jy. At 5 GHz, fringe amplitudes to VSOP were 1–3 Jy. Residual fringe rates varied smoothly between 0 and 90 mHz at 1.6 GHz and between −50 and 400 mHz at 5 GHz. The maximum residual fringe rate corresponds to a coherence loss of ~3% in an 0.1 s integration. Measured decorrelation over 60 s at the time of maximum residual rate on the VSOP-Usuda baseline was 5.6% at 5 GHz. Residual fringe delays varied smoothly between 150 and 550 ns at 1.6 GHz and between 0 and 400 ns at 5 GHz.

2.2. Calibration, Imaging, and Model Fitting

We show in Table 1 the system temperature and gain information used for each antenna. System temperatures for HALCA were measured during tracking passes adjacent to the observations and varied by less than 10% over an entire orbit. Gain information for HALCA was taken from calibration observations of Cygnus A during the period 1997 October 21 to November 4.

Data were averaged to 5 minutes before imaging and self-calibration. Imaging and modeling were performed with DIFMAP (Shepherd, Pearson, & Taylor 1994). The solutions converged quickly, and fits to all baselines were good. Amplitude scaling factors determined through self-calibration are also included in Table 1. Only for the case of Mopra at 5 GHz were the corrections greater than 20%. We fit models to the self-calibrated visibility data (Table 2). We show in Figure 2 the visibility amplitude at 5 GHz as a function of $u$-$v$ distance along with circular Gaussian models that bracket the best-fit model.

We have confidence in the 5 GHz amplitude self-calibration. First, we note that fits to the 1.6 and 5 GHz data prior to amplitude self-calibration were consistent with those for the self-calibrated data. Second, without input of the zero-baseline flux, the amplitude self-calibration reduced the flux on the Mo-
pra-AT baseline ($b \approx 2M\lambda$) from 9.86 ± 0.1 to 7.48 ± 0.06 Jy. This latter value is consistent with a single-dish measurement made in the same epoch (see below). The flux missing between this short baseline and the longer baselines (≈3.8 Jy) must be contained in structures with an angular size in the range 8–100 mas (2M\lambda < b < 25M\lambda). VLBI imaging at 8.4 GHz shows multiple structures with ∼2 Jy with a FWHM of $b \approx 25M\lambda$ (Bower et al. 1998). If the flux and the size are proportional to wavelength, then the missing flux is accounted for.

2.3. Contemporaneous Spectrum

The University of Michigan Radio Astronomy Observatory reports observations of NRAO 530 within two weeks of the VSOP observations. They find fluxes of 7.34 ± 0.13, 8.49 ± 0.11, and 7.49 ± 0.06 Jy at 4.8, 8.0, and 14.5 GHz. Observations with the Berkeley-Illinois-Maryland Association millimeter interferometer give a flux of ∼5 Jy at 86 GHz in the same epoch. We assume for the remainder of the Letter that the spectrum has a self-absorption turnover at 8 GHz with a flux of 8.5 Jy and a high-frequency spectral index of $\alpha = -0.2$ for $S \propto \nu^\alpha$.

3. DISCUSSION

3.1. Comparison with Other Observations

We tabulate the brightness temperatures of each of the components in Table 2 using the expression

$$T_b = 1.41 \times 10^9 \text{K} \times (1 + z) \left(\frac{S}{\text{Jy}}\right) \left(\frac{\sigma_1}{\text{mas}}\right)^{-1} \left(\frac{\lambda}{\text{cm}}\right)^2,$$

(1)

where $z$ is the cosmological redshift of the source, $S$ is the peak flux density, $\sigma_1$ and $\sigma_2$ are the FWHM sizes of the component in major and minor axes, and $\lambda$ is the observed wavelength. This and all subsequent brightness temperatures are given in the rest frame of the host galaxy.

The 5 GHz brightness temperature is the highest ever measured for NRAO 530 and is among the highest measured interferometrically. Previous space VLBI observations of NRAO 530 with the TDRSS satellite at 15 GHz found $T_b = 9 \times 10^{11}$ K (Linfield et al. 1990). Previous 3 mm VLBI observations found a brightness temperature of $4 \times 10^{11}$ K at the peak of the millimeter flare (Bower et al. 1997). Contemporaneous measurements with the VLBA at 22 and 43 GHz give brightness temperatures of $4 \times 10^{11}$ and $2 \times 10^{11}$ K, respectively (Bower et al. 1998). Given the limits to ground-based brightness temperatures, these values also represent lower limits to the brightness temperature. These observations also indicate that the structure on submillisecond scales has two components. The 1.6 and 5 GHz brightness temperatures are, therefore, lower limits to the actual brightness temperature.

3.2. Extrinsic Effects on the Brightness Temperature

NRAO 530 is at a low galactic latitude in the direction of the Galactic center ($l = 12^\circ, b = +11^\circ$) and, hence, may be affected by significant interstellar scattering. The expected scattering size scales as $\lambda^{2.2}$ (Taylor & Cordes 1993). This is marginally consistent with the power-law index of the measured core sizes, $1.5 \pm 0.2$. The expected scattering sizes are 1.8 mas at 1.6 GHz and 0.16 mas at 5 GHz. Since the scattering sizes and the measured sizes are comparable and there is a large uncertainty in the scattering sizes, we cannot reliably remove their effects. We conclude that the measured sizes at 1.6 and 5 GHz are near the minimum observable at this flux density and that the brightness temperatures are lower limits to the intrinsic brightness temperature.

3.3. Intrinsic Causes for Excess Brightness Temperature

We can compare the observed brightness temperatures to the limits imposed by intrinsic physical processes. We consider first processes associated with a homogenous sphere as discussed by Readhead (1994): the IC catastrophe and an unspecified mechanism that maintains equipartition of energy. Later, we will consider the limits imposed by an inhomogeneous jet in energy equipartition. The IC catastrophe imposes a limit of $T_b \approx 5 \times 10^{11}$ K. The equipartition requirement imposes a limit of $T_b \approx 0.5 \times 10^{11}$ K. These values are quite robust; they depend only weakly on the spectral parameters of the component.

The 5 GHz component significantly exceeds both of these limits. Doppler factors of 6 and 60 are necessary to accommodate the limits, respectively. We estimated previously through component proper motion studies at millimeter wavelengths that $\beta_{\text{ap}} \approx 7h^{-1}$ (Bower et al. 1997) and have since refined this value through more extensive monitoring to $\beta_{\text{ap}} \approx 4h^{-1}$ (Bower et al. 1998). We also estimated previously through synchrotron self-Compton arguments that $\delta > 11$ and through gamma-ray opacity arguments that $\delta > 2.3$. If we require that the apparent velocity be $4h^{-1}c$, we find $\theta = 8.29$ and $\gamma = 4.4$ for $\delta = 6$ and $\theta = 0.1$ and $\gamma = 30$ for $\delta = 60; \theta$ is the angle between the jet and the line of sight, and $\gamma$ is the bulk Lorentz factor.

A Lorentz factor of 30 is at the limit of what can exist under standard jet and accretion disk parameters. Melia & Königl (1989) calculate that thermal radiation from an accretion disk produces a radiative drag on a jet that leads to terminal Lorentz factors on the order of 10. Further, objects with Lorentz factors large must be extremely rare since measured apparent velocities appear to have an upper limit of ∼10 (Vermeulen & Cohen 1994). We consider it more likely that the true Doppler boosting factor is ∼6 and that the limiting physical process in this component is the IC catastrophe.

If this is true, then the component is significantly far from the equipartition energy. Following Readhead, we calculate that the total energy exceeds the equipartition energy value by a factor of ∼10 and that the magnetic field is less than the equipartition value by a factor of ∼10. The particle energy density exceeds the field energy density by a factor of ∼10. These conditions are far from what one expects under the typical magnetized shock-in-jet scenario for the acceleration of relativistic electrons.

We now consider a third intrinsic explanation: an inhomogeneous jet in energy equipartition. In this case, the brightness temperature limit is $3 \times 10^{11}\delta^{5/6}$ K (Blandford & Königl 1979). This limit is higher because of the special geometry of the inhomogeneous jet, which leads to a more peaked distribution of the flux than in the case of the homogeneous sphere. The implied Doppler boosting factor is then ∼15, and $\theta \approx 2.5$ and $\gamma \approx 9$. The expected size for such a jet at 5 GHz is ∼0.5 mas, in excellent agreement with our observations. The implied magnetic field strength at the radius of maximum brightness temperature is 0.01 G, and the total jet power is $7 \times 10^{45}$ ergs s$^{-1}$.

We have securely measured a brightness temperature in excess of $10^{12}$ K in the gamma-ray blazar NRAO 530 through observations with the VSOP orbiting radio telescope. This is

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1 Posted by H. Aller & M. Aller and available at http://www.astro.lsa.umich.edu/obs/radiotel/umrao.html.
strong evidence for beamed relativistic motion in a jet. We have considered several intrinsic causes for this extreme brightness temperature. We favor the inhomogeneous jet model of Blandford & Königl (1979), which produces a reasonable Doppler boosting factor while maintaining energy equipartition. The equipartition brightness temperature limit of Readhead does not apply in this situation due to the extreme Doppler boosting factor required. Although this limit appears to apply in many other sources, variability in NRAO 530 may allow departures from this equipartition limit on timescales of a few years or more. If the brightness temperature is limited by the IC catastrophe in a homogeneous sphere, then the implied Doppler boosting factors are more reasonable. However, the departures from energy equipartition are difficult to understand. On the other hand, this scenario is favorable because it provides a link between the millimeter and centimeter wavelength variability and the gamma-ray activity observed in NRAO 530. One can speculate that blazars detected by EGRET are those in which the equipartition brightness temperature limit is briefly superseded by the IC catastrophe limit. Space VLBI observations with VSOP and with future missions such as *ARISE* (Ulvestad & Linfield 1998) will be necessary to probe the physical limits on high brightness temperature sources.

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