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SEARCH FOR ELECTRON-POSITRON ANNIHILATION RADIATION FROM THE JET IN 3C 120

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ABSTRACT

We report an attempt to detect the electron-positron annihilation line from the radio galaxy 3C 120, in which the jet interacts strongly with interstellar clouds. Such interactions should cause most of the jet plasma to mix with the gas in the clouds. This will thermalize the majority of any positrons in the jet, leading to continuous annihilation with ambient electrons. We derive the number density of the combined electron-positron population in the core and compact knots in the jet of 3C 120 using ultrahigh-resolution observations with the Global millimeter-VLBI Array at 86 GHz and the Very Long Baseline Array at 43 GHz, along with the millimeter-wave continuum spectrum and a computational code that maps the synchrotron intensity of a model jet. If the jet contains a pure pair plasma, the production rate of positrons required to produce this density plus the efficiency of eventual annihilation predict the emission of a narrow spectral line at a rest energy of 511 keV, or 495 keV in the observer's frame. Our spectral observations with the SPI instrument on *INTEGRAL* failed to detect the line. The upper limit, which is 30% lower than our rather uncertain prediction, does not significantly constrain the positron-to-proton ratio in the jet of 3C 120. However, our procedure provides a robust method for determining the flux of electrons and positrons in a jet that will be useful when more sensitive soft γ-ray spectrometers and millimeter-wave VLBI arrays become available.

Subject headings: galaxies: active — galaxies: individual (3C 120) — galaxies: jets — gamma rays: observations — radio continuum: galaxies

1. INTRODUCTION

The matter content of jets, mostly e^+-e^- pairs or completely "normal" e^--p^+ plasma, is one of the most important issues in the physics of active galactic nuclei (AGN), yet has remained unresolved despite many years of effort. The composition of a jet is intimately related to the physical processes that create and energize it (e.g., Blandford & Levinson 1995; Sikora & Madejski 2000). The creation of pairs would probably involve strong interactions between the jet and photons produced in the accretion disk and immediate surroundings (e.g., Blandford & Levinson 1995; Reynolds et al. 1996; Sikora & Madejski 2000). Confirmation that the jet is mainly composed of pairs would therefore lead to tighter constraints on models for the creation, acceleration, and collimation of the jet between the accretion disk and the "core" of the radio emission.

The issue is extremely controversial, with various attempts to determine the answer by indirect means leading to contradictory conclusions (e.g., Celotti & Fabian 1993; Reynolds et al. 1996; Sikora & Madejski 2000; Wardle et al. 1998; Ruszkowski & Begelman 2002; Celotti 2003; Hirotani 2005). The most direct method is to detect, or fail to detect at the level predicted for an e^+-e^- dominated jet, the emission line from e^+-e^- annihilations. Unfortunately, inside a jet the relativistic bulk and internal motions both decrease the cross section to annihilation and broaden the line so much that it becomes a broad bump in the continuum (Böttcher & Schlickeiser 1996) that could be interpreted in other ways. The situation is changed, however, if the material in the jet mixes with dense thermal gas, as expected when the jet strikes a cloud. Such jet-cloud interactions are occurring in the $z = 0.033$ Fanaroff-Riley Class I radio galaxy 3C 120, as indicated by absorption and strong Faraday rotation (Gómez et al. 2000, hereafter G00). The inferred density of the cloud $\gtrsim 5 \times 10^4$ cm^{-3} (G00), intermediate between that of a broad emission line cloud and a narrow emission line cloud.

If the jet is mainly composed of a pair plasma, the positrons from the part of the jet that strikes the cloud will enter the cloud and thermalize from "ionization" energy losses (ionizations plus various plasma effects) on a timescale $\tau_{\rm therm} \lesssim 0.6\gamma_i(5 \times 10^4\ {\rm cm}^{-3}/n_e)$ yr, where γ_i is the initial Lorentz factor of a typical positron as it enters the cloud. (We have used the standard formula for ionization losses given in Pacholczyk 1970.) The annihilation timescale $\tau_{\rm an} \sim 100(5 \times 10^4\ {\rm cm}^{-3}/n_e)$ yr (see, e.g., Furlanetto & Loeb 2002). These timescales are a factor of a few less than the time for the cloud to move out of the way of the jet in the nucleus of 3C 120 ($\gtrsim$300 yr for a cloud size $\sim$1 pc [G00] and velocity component transverse to the jet $\lesssim$3000 km s^{-1}). The steady-state annihilation rate should then correspond to the number of positrons impinging on the cloud per second. The line width, determined mainly by large-scale motions of the gas clouds, should be less than 3 keV.

In addition to the above-mentioned cloud in the nucleus, 3C 120 contains a large amount of kiloparsec-scale gas seen in various emission lines, especially that of [O III] (Baldwin et al. 1980). Hua (1988), Axon et al. (1989), and Sánchez et al. (2004) have presented convincing evidence that the jet/counterjet system interacts strongly with this gas, which Hua (1988) estimates to have a density in the range of 10^3–10^7 cm^{-3}. Therefore, a substantial fraction of any positrons in the jet eventually interact with dense gas, contributing to a narrow (by high-energy standards) annihilation line. Because of this, the relatively short distance to the radio galaxy (140 Mpc for $H_0 = 70$ km s^{-1} Mpc^{-1}), and the well-observed apparent superluminal motion requiring a flow

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Lorentz factor $\Gamma = 5$–6 (G00; Jorstad et al. 2005, hereafter J05), 3C 120 is an excellent candidate for observing the 511 keV (redshifted to 495 keV) annihilation line among AGN with relativistic jets.

Here we report an upper limit to the annihilation-line flux from 3C 120 derived from a hard X-ray/soft γ-ray spectrum obtained with the SPI spectrometer of the *INTEGRAL* space observatory (see Roques et al. 2003). We compare this with the flux predicted based on the electron-positron density of the millimeter-wave core of the jet as determined by very long baseline interferometry (VLBI) observations at 86 GHz with the Global millimeter-VLBI Array (GMVA) and at 43 GHz with the Very Long Baseline Array.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *INTEGRAL Observations*

We observed a field centered on 3C 120 with the SPI instrument (Vedrenne et al. 2003; Roques et al. 2003) for about 500 ks in 2005 August. The observations included a standard 5×5 dither to sample the background for eventual subtraction from the primary source spectrum. The observations were divided into 144 separate pointings.

The data analysis followed the prescription of the online SPI Cookbook found at the *INTEGRAL* home page.[6] We performed image reconstruction of the 0.1–1 MeV continuum with the SPIROS software using background method 5 (also known as "MCM"), a procedure that generated residual images for each pointing. This produced far superior results compared with the other recommended choice, background method 2, with the latter producing fluctuations above the 3 σ noise level for 93 of the pointings, compared with only 41 for method 5. The pointings with high fluctuations were removed from the analysis. The final background-subtracted image revealed the Crab pulsar in the northeast corner of the field as the only significant continuum source, detected at 6.8 σ above the noise level.

We then used SPIROS and the X-ray spectral fitting program XSPEC (Arnaud 1996) with the standard SPI response matrices (Sturner et al. 2003) to produce a spectrum of the background-subtracted data from 200 to 1000 keV, with 4 keV energy bins, at the position of 3C 120. We display the spectrum in Figure 1. The continuum produced only a slight excess above the zero level. If we fit it with a power law and subtract the resultant model, the line flux at 495 keV increases by about 10%, whereas subtraction of channels containing instrumental lines does not alter the flux. There are no known instrumental lines at 495 ± 7 keV (Jean et al. 2003). The measured line flux is therefore $(1.1 \pm 1.1) \times 10^{-5}$ photons cm^{-2} s^{-1} within the 4 keV channel centered on 495 keV. (As is discussed in § 1, we expect that the width of any annihilation line from interaction between the jet and clouds in 3C 120 would be less than about 3 keV.) The 2 σ upper limit to the annihilation line is therefore 3.3×10^{-5} photons cm^{-2} s^{-1}.

2.2. 86 *and* 43 GHz *VLBI Observations*

In 2004 October we carried out VLBI observations of 3C 120 at the highest routinely available frequencies, 86 and 43 GHz. Figure 2 presents the images that resulted from the following procedures.

The 86 GHz observations with the GMVA[7] took place on 2004 October 12 with the standard data recording mode 512-8-2.

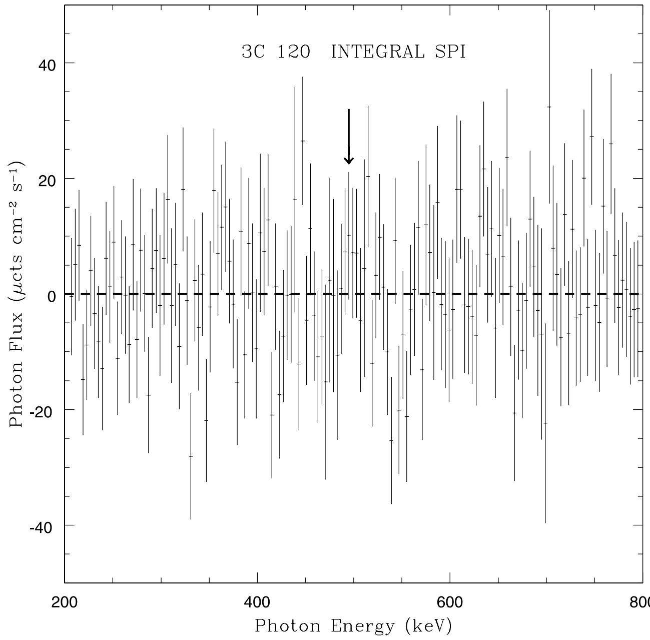

FIG. 1.—*INTEGRAL* SPI spectrum of 3C 120. The downward arrow in the upper middle indicates photon energy 495 keV, the redshifted energy of the 511 keV annihilation line.

The array included the Max-Planck-Institut für Radioastronomie (MPIfR) 100 m radio telescope in Effelsberg, Germany; the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope in Granada, Spain, and phased 6×15 m interferometer at Plateau de Bure, France; the Onsala Space Observatory 20 m antenna in Onsala, Sweden; the Metsähovi Radio Observatory 14 m antenna in Kylmää, Finland; and eight of the ten 25 m antennas of the Very Long Baseline Array (VLBA; the antennas at St. Croix and Brewster, Washington were not equipped for 86 GHz observations). The data from the different antennas were correlated at the MPIfR in Bonn, Germany. Subsequent calibration was accomplished with the Astronomical Image Processing Software (AIPS) distributed by the National Radio Astronomy Observatory (NRAO). We used the Difmap software distributed by Caltech (see Shepherd 1997) to make the images and perform the final calibration.

We observed 3C 120 at 43 GHz on 2004 October 28 with all 10 VLBA antennas, although the telescope at Pie Town, New Mexico participated only during the final 20 minutes. The data were correlated at NRAO in Socorro, New Mexico. Otherwise, the processing and analysis proceeded in a manner similar to that at 86 GHz described above.

After making the final images, we used the Difmap model fitting option to describe the source in terms of a small number of components with elliptical Gaussian brightness distributions. The best-fit models, generated independently, provide excellent agreement in the most compact structure evident at both frequencies: core on the eastern end plus a series of knots delineating a jet extending to the west. The flux density of the core is 0.28 Jy and 0.43 Jy at 86 and 43 GHz, respectively, with uncertainties of about 20% that are dominated by systematic errors in the flux scales. The 86 GHz image (see Fig. 2) reveals a knot with flux density 0.09 Jy 63 μas from the core that is blended with the core at 43 GHz. We therefore use the 86 GHz data to define the properties of the core. The core is unresolved in the transverse direction at 86 GHz, but partially resolved along the direction of the jet. In this direction, the angular size (FWHM) of the core is 22 ± 2 μas. (The ratio of the correlated flux density of

[6] See http://isdc.unige.ch.

[7] See http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm for a description.

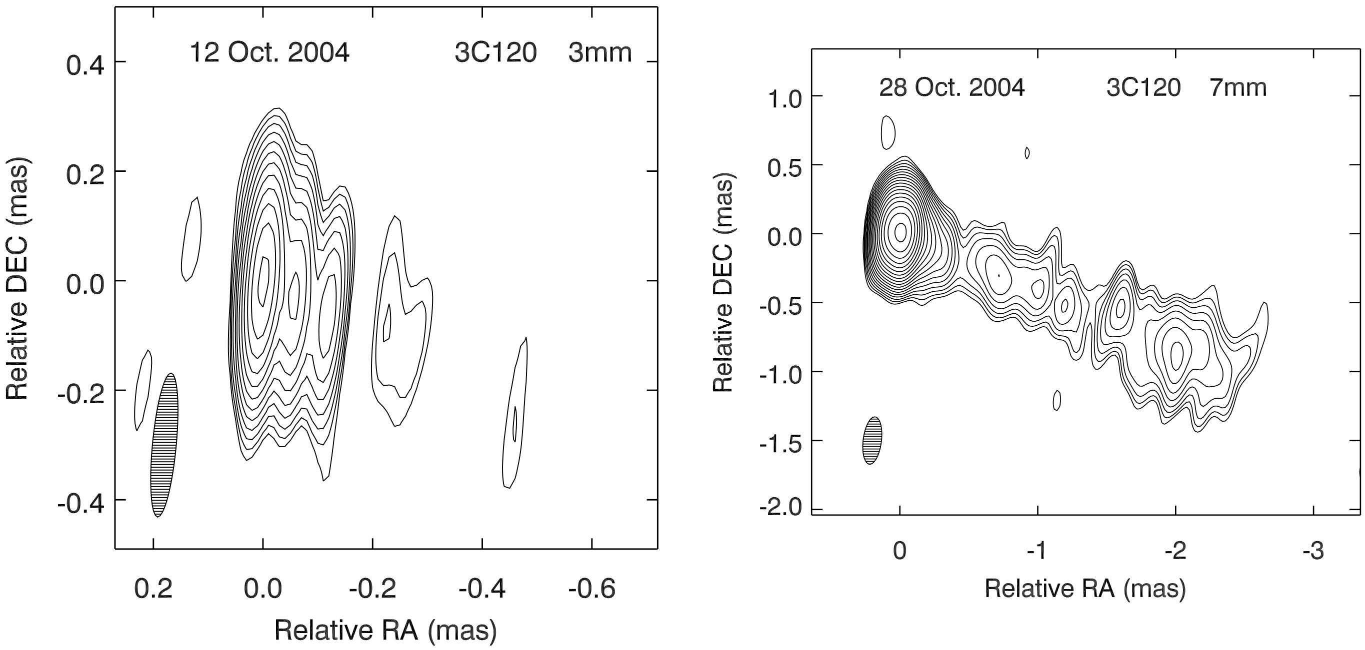

Fig. 2.—VLBI images of 3C 120 at millimeter wavelengths. The elliptical restoring beam is shown in the lower left corner of each figure. *Left*: Global millimeter-VLBI Array image at 86 GHz (0.35 mm) on 2004 October 12. Contours start at 2% of the peak intensity of 0.25 Jy beam^{-1} and increase by factors of $\sqrt{2}$. The beam has FWHM dimensions of 0.26×0.043 mas, oriented 5° clockwise from north–south. *Right*: VLBA image at 43 GHz (0.69 mm) on 2004 October 28. Contours start at 0.25% of the peak intensity of 0.278 Jy beam^{-1} and increase by factors of $\sqrt{2}$. The beam is 0.34×0.13 mas with major axis 7° clockwise from north–south.

the core measured by the longest baseline of the GMVA to its full flux density is 0.67, which is sufficiently less than unity to determine the angular size accurately. It is possible, however, that the core contains multiple components that are even smaller, in which case the value of the electron-positron flux would be higher than that derived below.) Here the uncertainty is based on modifications to the core size in the model fit that cause the χ^2 statistic of the longest baselines (those sensitive to the details of the most compact structure) to become unacceptable at the 95% confidence level. Similarly, we find that the FWHM angular extent of the knot 0.13 mas from the core (see Fig. 2) is no larger than 30 μas in the direction transverse to the jet axis.

3. PREDICTED FLUX OF THE ANNIHILATION LINE

3.1. *Flux of Positrons and Electrons in the Core*

We can analyze the radio data of the core of 3C 120 to determine the combined density of relativistic electrons and positrons. This method makes use of standard formulas of synchrotron radiation (e.g., Pacholczyk 1970) from a region whose emission is self-absorbed below a frequency within the observed range. Marscher (1983) gives the formulas with corrections for redshift and Doppler beaming, calculated for a uniform spherical source with magnetic field B and electron-positron number density per unit energy $N(E) = N_0 E^{-s}$. This analysis provides separately the values of the magnetic field B and N_0 without making any assumptions about the ratio of energy densities in particles and field.

The observational parameters required by this method are the angular diameter, the synchrotron self-absorption turnover frequency ν_m of the continuum spectrum, the flux density F_m at this frequency, the spectral index $\alpha = (s - 1)/2$ (defined as $F_\nu \propto \nu^{-\alpha}$) above the turnover, the redshift (0.033), the luminosity distance (140 Mpc), the Doppler beaming factor ($\delta = 2.4 \pm 0.4$; J05), and the angle between the jet axis and the line of sight (20°; J05). Our measured flux densities of the core at 43 and 86 GHz are compatible with $\nu_m \approx 70$ GHz measured 12 years earlier by Bloom et al. (1994, 1999), so we adopt this value. The same authors measure the spectral index above this frequency to be 0.8 ± 0.05, which is higher than the value of 0.65 measured in knots farther downstream (Walker et al. 1987). We adopt $\alpha = 0.75$ as the lowest value compatible with the millimeter-wave flux density measurements and $F_\nu = 0.28$ Jy at 86 GHz. (The VLBI observations occurred during a period of weak variability at high radio frequencies according to the 37 GHz light curve measured at the Metsähovi Radio Observatory; hence the 16 day offset of our 43 and 86 GHz VLBI observations does not present a problem in our analysis.)

A proper derivation of the physics parameters requires replacement of the uniform, spherical geometry adopted by Marscher (1983) with a more realistic jet model, in which the density, energy per electron, and magnetic field decrease with distance down the jet (see Königl 1981; Marscher 1995 for the standard model and discussion). In general, the spectra of cores are not exactly flat below the turnover as in the Königl (1981) formulation (see, e.g., Bach et al. 2006 for a well-documented example), and so we adopt the adiabatic jet model of Marscher (1980) in the region, where the Lorentz factor of the jet flow is constant and a conical geometry applies. We then obtain a dependence of N_0 on distance r from the vertex of the jet of $N_0 \propto r^{-(2\alpha+3)/2}$, or $N_0 \propto r^{-3}$ for $\alpha = 0.75$. As in the standard jet model of Königl (1981) we adopt the relationship $B \propto r^{-1}$. We have created a FORTRAN computer code that calculates the intensity of synchrotron radiation as a function of projected position in the jet, taking into account the optical depth to self-absorption and the variation of the Doppler factor with the angle between each streamline and the line of sight. We truncate the emission inside a distance r_0 of the vertex of the cone. This is in concert with the recent finding by D'Arcangelo et al. (2007) that the core of the quasar 0420−014 contains at its inner boundary a standing shock that energizes the radiating electrons. We also truncate the emission 0.032 mas downstream of the peak of intensity, halfway between the centroids of the core and the first knot seen on the 86 GHz image (see Fig. 2). In order to match the 86 GHz VLBI data, we calculate the fringe visibility amplitude of the model source and compare it to the observed value. We constrain the size scale of the core such that if the ambient jet were to extend out to 0.13 mas from the brightness peak, it would match the transverse size of the knot at that location. That is, the visibility amplitude in the transverse direction would equal that of a Gaussian source of FWHM = 0.03 mas. We modify the free parameters r_0, $B(r_0)$, and $N_0(r_0)$ until the flux density, self-absorption turnover frequency, and fringe visibility amplitude equal the observed values. Our final best-fit values are $r_0 = 0.036$ pc, $B(r_0) = 0.23$ G, and $N_0(r_0) = 0.008$ erg$^{1.5}$ cm^{-3}.

The proper-frame density of electrons plus positrons is given by $n(e^+ + e^-) = (2\alpha)^{-1} N_0 E_{\rm min}^{-2\alpha} = 7.2 \times 10^6 \gamma_{\rm min}^{-1.5}$, where $E_{\rm min} = \gamma_{\rm min} mc^2$ is the minimum energy of the power-law distribution of relativistic electrons and positrons. The cross-sectional radius of the jet at the core is $R_0 = 7.4 \times 10^{15}$ cm. If a fraction $0.5f$ of the species are positrons, their flux from both the jet and counterjet (which we presume to be essentially identical to the visible jet and also to collide with clouds; see Axon et al. 1989 for evidence that this occurs) is, in the rest frame of the host galaxy,

$$F(e^+) = \pi R_0^2 c f \Gamma n = 2 \times 10^{50} f \gamma_{\rm min}^{-1.5} \text{ positrons s}^{-1}, \quad (1)$$

where we have adopted $\Gamma = 5.3$ from J05.

The corresponding rate of rest-frame energy production of electrons and positrons is $6 \times 10^{43} f \gamma_{\rm min}^{-0.5}$ erg s^{-1}, a few times less than the X-ray luminosity (Marscher et al. 2002) if $f \gamma_{\rm min} \approx 1$. This suggests a roughly comparable amount of energy devoted to particle production in the jet as to heating in the accretion disk/corona system, which is responsible for the bulk of the X-ray emission. On the other hand, the particles contain a factor of $\sim 10^4$ times more energy than does the magnetic field in the core. We note that Kovalev et al. (2005) have derived a similar departure from equipartition conditions somewhat farther downstream in the compact jet of 3C 120, based on VLBA observations at 15 GHz. At this frequency the "core" on VLBI images is probably the surface, where the optical depth is roughly unity (Königl 1981).

Hirotani (2005) used a similar method to determine the density of radiating particles in the jets of the quasars 3C 279 and 3C 345. However, he carried out the full analysis only for bright knots, while in the cores he lacked sufficient observational data to do so, instead assuming equipartition between the magnetic and particle energy densities. The properties of the core should represent the mean ambient flow of the jet that we expect to be relevant to the rate of injection of particles into the surrounding medium. We therefore designed our study to avoid the equipartition assumption when evaluating the density in the core of 3C 120.

3.2. *Expected Flux of the Annihilation Line*

We can use equation (1) to calculate the predicted steady-state flux of the annihilation line from 3C 120 at a rest energy of 511 keV, which is redshifted to 495 keV in our frame. We assume that a fraction x of positrons in the jet mix with clouds in the host galaxy, thermalize, and annihilate with ambient electrons there. The annihilation-line flux is then

$$F(\text{line}) = 4.3 \times 10^{-5} f x \gamma_{\rm min}^{-1.5} \text{ photons cm}^{-2} \text{ s}^{-1}. \quad (2)$$

Here, we have used a multiplicity of 1/2, since one out of every four annihilations after positronium formation produces two photons at 511 keV (e.g., Bussard et al. 1979).

As discussed in § 1, we infer from the observations that most of the electrons and positrons in the jet of 3C 120 mix with clouds in the interstellar medium, so that $x \sim 0.5$–1. We also note that the rate of energy production in particles in the jet in regions much farther from the core, estimated by Walker et al. (1987) on the basis of equipartition arguments, is significantly lower than the value we calculate close to the core of the jet. Such a decline with distance from the core is consistent with strong interaction between the jet and gas in the surrounding medium. The apparent bending of the jet by tens of degrees on scales from milliarcseconds to arcseconds (Walker et al. 1987) requires actual (i.e., in three dimensions) bending by at least $\sim 10°$ (calculated by adopting a viewing angle near the core $\sim 20°$; J05), which implies a substantial degree of momentum transfer from the relativistic flow to the external medium. In general, jets of FR I radio galaxies are thought to interact strongly with the environment (e.g., De Young 1993). Since we do not expect interstellar clouds to contain magnetic fields of insufficient strength and order to deflect particles from the jet, substantial mixing of jet material with thermal gas should occur at each point of interaction. Although standing oblique shocks will deflect much of the jet flow, multiple interactions as seem to occur in 3C 120 should cause most of the jet particles to mix with clouds. Although some of the jet continues beyond the boundaries of the cloudy region, it weakens considerably as it does so (see, e.g., Harris et al. 2004).

We also argue that the minimum Lorentz factor of the electron-positron population is probably $\gamma_{\rm min} \approx 1$ if the jet is composed completely of pairs. Otherwise, the internal energy of the plasma would be much greater than the rest-mass energy density. The bulk Lorentz factor would then increase in the downstream direction as internal energy is converted into flow energy (Blandford & Rees 1974), and the apparent motion of knots in the jet would accelerate outward. Instead, the apparent speed remains in the 4–5 c range from subparsec scales to tens of parsecs from the core (J05; Gómez et al. 2001; Walker et al. 1987). If, on the other hand, the number of protons in the jet is at least $m(e)/m(p) = \gamma_{\rm min}/1836$ times the number of positrons, then the jet will be rest-mass dominated, and therefore its velocity will not increase with distance down the jet. The limit on $\gamma_{\rm min}$ is therefore $\gamma_{\rm min} \lesssim 1836(1 - f) + 1$.

Despite our detailed observations, the use of a realistic jet model to calculate the electron plus positron flux in 3C 120, and attempt to be conservative in our estimates of the observational parameters, the uncertainties in the method are substantial. We have determined the error in angular size of the core to be 10% along the jet direction (an upper limit is used in the transverse direction), and the assumed values of Γ, ν_m, and F_m are accurate only to about 20%, 15%, and 15%, respectively. Propagation of errors plus the requirements $x < 1$ and $\gamma_{\rm min} > 1$ yield a combined uncertainty of about a factor of 10.

Our upper limit to the annihilation-line flux falls only 30% below the predicted value even if x and $\gamma_{\rm min}$ are close to unity and uncertainties in the prediction are ignored. Our observations therefore do not constrain the positron fraction significantly. However, it is evident that a more sensitive soft γ-ray spectrometer should be able to do so, especially if combined with simultaneous multifrequency VLBI observations with higher signal-to-noise ratios than can be achieved currently.

4. CONCLUSIONS

We have failed to detect the reshifted e^+-e^- annihilation emission line toward the radio galaxy 3C 120, where we have reason to believe that the jet interacts strongly with clouds in the interstellar medium. This should cause any positrons present to thermalize and annihilate with ambient electrons to produce a narrow ($\lesssim$3 keV) line. Our upper limit is less than 2 times lower than our prediction, which contains substantial uncertainties owing to errors in observational parameters. Our value of the expected flux also depends on the assumptions that most of the putative positrons eventually annihilate in the interstellar medium, and that the minimum energy of the electron-positron population is about the rest-mass value, both of which have observational support.

The main value in our work is to elucidate the most accurate method for determining the combined flux of electrons and positrons in the ambient jet through millimeter-wave VLBI observations. Such observations obtained during relatively quiescent periods in the nonthermal emission from the AGN and analyzed within a conical jet model provide the values of the magnetic field, cross-sectional radius, and electron energy distribution parameter N_0 at the base of the core seen on the VLBI images. The latter two determine the electron-positron flux needed to estimate the flux of annihilation-line radiation from the AGN for a given positron-to-proton ratio.

Although it is more sensitive than previous detectors, the flux limit that can be obtained with a reasonable exposure time on the SPI instrument on *INTEGRAL* is insufficient to detect the annihilation line from 3C 120 at greater than the $\sim$1 σ level. Future generations of soft γ-ray spectrometers and millimeter-wave VLBI arrays with sensitivities better than currently available are required to place significant limits on the positron content of jets in AGNs.

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