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IS THE SUPERNOVA REMNANT RX J1713.7−3946 A HADRONIC COSMIC-RAY ACCELERATOR?

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ABSTRACT

The nonthermal supernova remnant (SNR) RX J1713.7−3946 has recently been shown to be a site of cosmic-ray (CR) electron acceleration to TeV energies. Here we present evidence that this remnant is also accelerating CR *nuclei*. Such energetic nuclei can interact with ambient interstellar gas to produce high-energy gamma rays via the decay of neutral pions. We associate the unidentified EGRET GeV gamma-ray source, 3EG J1714−3857, with a very massive (~$3 \times 10^5\ M_\odot$) and dense (~500 nucleons cm^{-3}) molecular cloud interacting with SNR RX J1713.7−3946. Direct evidence for such interaction is provided by observations of the lowest two rotational transitions of CO molecules in the cloud; as in other clear cases of interaction, the CO ($J = 2 \rightarrow 1$)/CO ($J = 1 \rightarrow 0$) ratio is significantly enhanced. Since the cloud is of low radio and X-ray brightness, electrons cannot be responsible for the bulk of the GeV emission there. A picture thus emerges in which both electrons and nuclei are being accelerated by the SNR: whereas the relativistic electrons dominate the *local* nonthermal radio, X-ray, and TeV emission, the shock-accelerated CR protons and ions (hadrons) are exposed through their interactions in the *adjacent* massive cloud, leading to the observed GeV emission via the gamma decay of neutral pions.

Subject headings: acceleration of particles — cosmic rays — ISM: clouds — supernova remnants

1. INTRODUCTION

The question over the origin of cosmic rays (CRs) has persisted ever since they were first detected in 1912 by Victor Hess using a balloon-borne electroscope device (Hess 1912). Despite the fact that there is now broad consensus that the shocks in the expanding blast waves of supernova remnants (SNRs) accelerate the bulk of the CR ions up to energies of ~300 TeV nucleon^{-1}, and possibly even to ~10^5 TeV nucleon^{-1} (Bell & Lucek 2001), direct evidence of this scenario has so far eluded observers. The best way to identify such energetic CR accelerators is to look for the associated high-energy gamma rays produced at the sources; however, since CR electrons and nuclei can both generate gamma rays at the acceleration sites, it has not yet been possible to unambiguously associate the detected gamma radiation with sources of CR *nuclei* specifically. In fact, only very recently have ground-based imaging air Cerenkov gamma-ray telescopes provided direct evidence for the presence of highly relativistic TeV energy particles, most likely electrons, at the shocks of three shell-type SNRs: SN 1006 (Tanimori et al. 1998), Cassiopeia A (Aharonian et al. 2001), and RX J1713.7−3946 (also known as G347.3−0.5; Muraishi et al. 2000), the remnant considered here. Even though previous reports (e.g., Sturner, Dermer, & Mattox 1996; Esposito et al. 1996; Gaisser, Protheroe, & Stanev 1998; Aharonian & Atoyan 1999; Combi, Romero, & Benaglia 1998; Combi et al. 2001) have suggested that the gamma-ray emission seen in the directions of some SNRs could be due to hadronic interactions, it has not been possible to rule out energetic electrons or the nearby pulsars as the dominant source of the detected radiation (e.g., Brazier et al. 1996; De Jager & Mastichiadis 1997; Gaisser et al. 1998).

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2. SOURCE 3EG J1714−3857 AND SNR RX J1713.7−3946

Prompted by the close association of the GeV EGRET source 3EG J1714−3857 (Hartman et al. 1999) with the TeV gamma-ray–emitting SNR RX J1713.7−3946, we have investigated the possibility that this remnant is also accelerating nuclei, *in addition to the known CR electron acceleration taking place there* (Muraishi et al. 2000). As Figure 1 shows, there are two massive and dense molecular clouds lying adjacent to the SNR, one of which, cloud A, immediately abuts the blast-wave region of the SNR (Slane et al. 1999). This cloud is also partially within the inner 50% confidence location contour of 3EG J1714−3857 (Hartman et al. 1999). Both clouds have a mean local standard of rest (LSR) velocity of −94 km s^{-1} and an inferred kinematic distance of 6.3 ± 0.4 kpc. The mass of cloud A is determined from CO observations (Bronfman et al. 1989) to be (3 ± 0.3) × $10^5\ M_\odot$, and its mean density is ~500 nucleons cm^{-3}. Cloud B has a mass of (2.8 ± 0.3) × $10^5\ M_\odot$ and a mean density of ~660 nucleons cm^{-3}.

As the blast wave of RX J1713.7−3946 overtakes cloud A, the shock-accelerated protons and ions collide with the resident nuclei and produce neutral pions that then promptly gamma-decay ($\pi^0 \rightarrow \gamma\gamma$), illuminating the cloud at GeV energies; such a scenario has been anticipated by several authors (e.g., Montmerle 1979; Aharonian, Drury, & Völk 1994; Dorfi 1991, 2000). Indeed, a recent detailed analysis of the broadband *electronic* emissions of RX J1713.7−3946 by Ellison, Slane, & Gaensler (2001) directly supports our findings by suggesting that 25%–50% of the forward-shock kinetic energy is likely being taken up in accelerating ions to relativistic energies of up to ~70 TeV nucleon^{-1} in this remnant. Strong evidence that the shock front of RX J1713.7−3946 has overtaken, and is interacting with, cloud A is provided by the enhanced intensity ratio of the two lowest rotational transitions of the CO molecules in the cloud, as already noted by Slane et al. (1999). This ratio, R = [CO ($J = 2 \rightarrow 1$)/CO ($J = 1 \rightarrow 0$)], is typically ~0.7 in the Galactic plane (Sakamoto et al. 1995) but is known to be enhanced in shocked molecular gas interacting with SNRs (e.g., Seta et al. 1998). We examined this ratio, R, at all LSR velocities over a 2° × 1° region centered roughly on cloud A, using CO ($J = 1 \rightarrow 0$) data from Bronfman et al. (1989) and unpublished

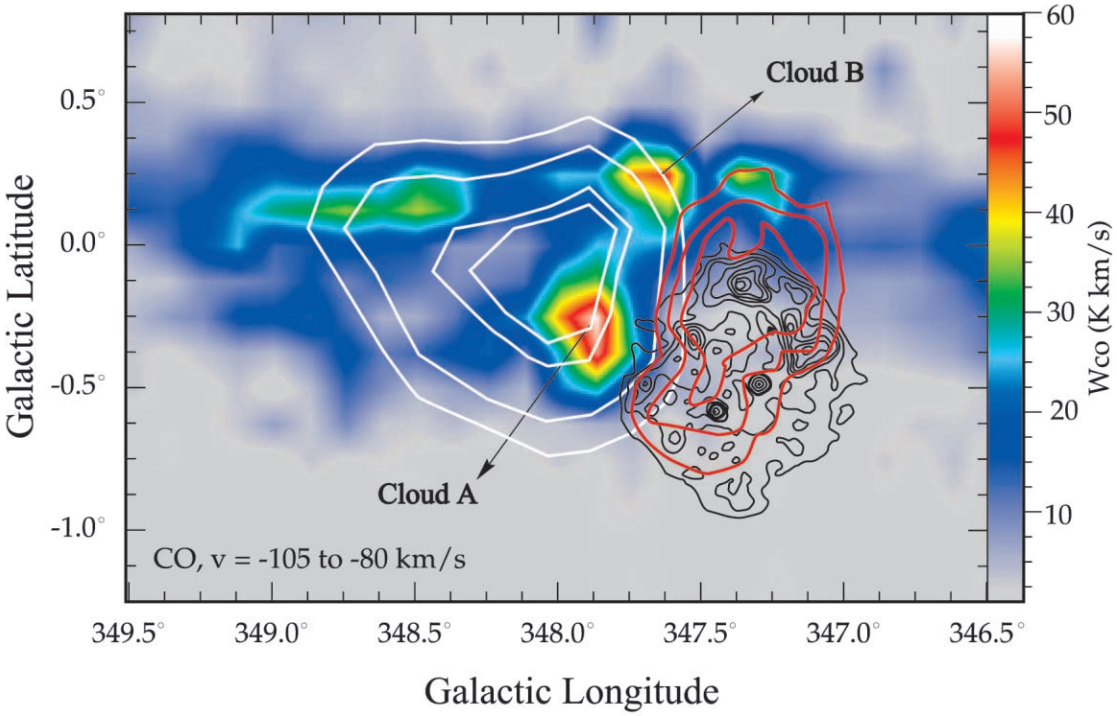


FIG. 1.—Overlay map in Galactic coordinates showing SNR RX J1713.7−3946 (G347.3−0.5) in gray (*ROSAT* PSPC X-ray) contours from Slane et al. (1999). The red depicts the TeV significance contours from Muraishi et al. (2000). In white are the location probability contours (successively, 50%, 68%, 95%, and 99%) of the GeV EGRET source 3EG J1714−3857 from Hartman et al. (1999). The color scale indicates the intensity of CO ($J = 1 \rightarrow 0$) emission, and consequently the column density of the ambient molecular cloud, in the LSR velocity interval $v_{lsr} = -105$ to -80 km s^{-1} associated with the SNR, corresponding to a kinematic distance of 6.3 ± 0.4 kpc. The elongated CO emission feature near $(l, b) \sim (348.^\circ5, +0.^\circ2)$ derives from the large velocity wings of a much more distant (~11.3 kpc) and unrelated cloud centered at $V_{lsr} = -68$ km s^{-1}.

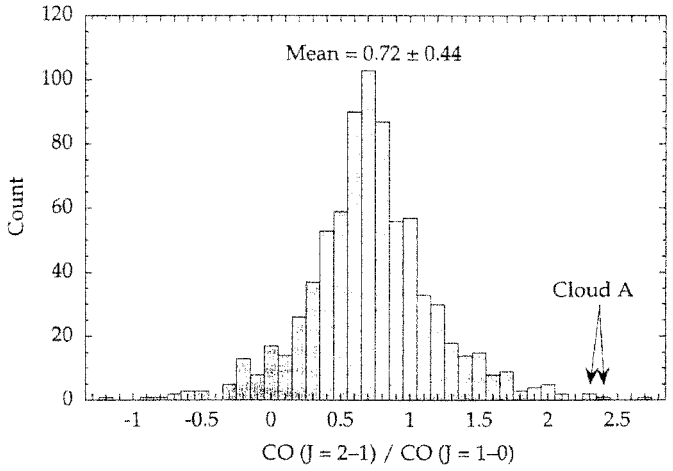


FIG. 2.—Distribution of all 781 line intensity ratios, $R = [\mathrm{CO}\ (J = 2 \rightarrow 1)/\mathrm{CO}\ (J = 1 \rightarrow 0)]$, measured every 15′ in the region $l = 346.^\circ5 \rightarrow 348.^\circ5$, $b = -0.^\circ5 \rightarrow +0.^\circ5$ and averaged over 5 km s^{-1} bins of velocity between $v_{lsr} = -150$ and 50 km s^{-1}. The pixels in which the CO ($J = 1 \rightarrow 0$) intensity is less than 2.5 times the instrumental noise are excluded. The bins labeled "Cloud A" contain 3 pixels, two of which are consistent with the position and velocity of cloud A: $(l, b, v) = (348.^\circ0, -0.^\circ25, -85$ km s$^{-1})$ and $(l, b, v) = (348.^\circ25, -0.^\circ5, -90$ km s$^{-1})$. All other pixels with high R-values ($R > 1.8$) lie well outside the 95% confidence location contour of 3EG J1714−3857. The mean of the distribution, ~0.72, agrees with the average unexcited value in the Galactic plane (Sakamoto et al. 1995). The dispersion about the mean of ~0.44 results both from the intrinsic scatter in R as well as from instrumental noise, mainly in the CO ($J = 2 \rightarrow 1$) data. That the latter source dominates is evidenced by some unphysical negative R-values that are caused by background subtraction in pixels with very low CO ($J = 2 \rightarrow 1$) intensity.

CO ($J = 2 \rightarrow 1$) data from the University of Tokyo 0.6 m telescope at La Silla, Chile, kindly provided by T. Handa and T. Hasegawa. As Figure 2 shows, of all the 781 ratios measured, two of the three highest (top 0.5%), with $R \sim 2.4 \pm 0.9$, were found on or very close to cloud A in both position and velocity. In contrast, no enhanced CO ($J = 2 \rightarrow 1$)/CO ($J = 1 \rightarrow 0$) ratio was observed in the vicinity of cloud B.

We have calculated the expected gamma-ray luminosity for the proposed scenario using the following information from Slane et al. (1999): supernova explosion energy $= E_{SN} = (1.7–2.2) \times 10^{51}$ ergs, distance to the SNR $= 6.3 \pm 0.4$ kpc, unshocked ambient density $n_0 = 0.01–0.3$ cm^{-3}, together with the cloud data extracted above. Using the Sedov solution, we calculate the age of the SNR to be in the range of $(2.5–13.4) \times 10^4$ yr. The total gamma-ray luminosity is divided between that from the hadronic interactions intrinsic to the SNR and that due to the enhanced probability of hadronic interactions in the high target-density medium of cloud A:

$$F_{\mathrm{tot}}(E > 100\ \mathrm{MeV}) = F_{\mathrm{snr}}(E > 100\ \mathrm{MeV}) + F_{\mathrm{cloud\ A}}(E > 100\ \mathrm{MeV}). \quad (1)$$

We may evaluate the first term as (Drury, Aharonian, & Völk 1994)

$$F_{\mathrm{snr}}(E > 100\ \mathrm{MeV}) \sim 4.4 \times 10^{-7} \times \theta E_{51} D_{\mathrm{kpc}}^{-2} n_0\ \mathrm{photons\ cm^{-2}\ s^{-1}}, \quad (2)$$

where θ is the fraction of the total supernova energy converted to CR energy, E_{51} is the supernova explosion energy in units of 10^{51} ergs, and $D_{\rm kpc}$ is the distance in kiloparsecs. If the start of the Sedov phase is taken at ~2400 yr, and $\theta \sim 0.5$ (e.g., Morfill, Forman, & Bignami 1984), then substituting the numerical values for the various quantities yields the intrinsic GeV luminosity of the SNR to be in the following range:

$$F_{\rm snr}(E > 100\ {\rm MeV}) = (0.1\text{–}3) \times 10^{-9}\ {\rm photons\ cm^{-2}\ s^{-1}}. \quad (3)$$

The second term represents the contribution to the GeV flux from the SNR-amplified CR bombardment of cloud A and is given by (Aharonian & Atoyan 1996)

$$F_{\rm cloud\ A}(E > 100\ {\rm MeV}) = 2.2 \times 10^{-7} M_5 D_{\rm kpc}^{-2} k_s\ {\rm photons\ cm^{-2}\ s^{-1}}, \quad (4)$$

where M_5 is the mass in units of $10^5\ M_\odot$ and k_s is the CR enhancement factor, i.e., the ratio of the CR energy density in the vicinity of the SNR to that measured near the Sun. [We adopt a gamma-ray emissivity, $q(E > 100\ {\rm MeV}) = 2.2 \times 10^{-25}$ photons (H atom)$^{-1}$ s^{-1}; Dermer 1986]. Using Morfill et al. (1984), we find that $24 < k_s < 36$ for the SNR at the current epoch. Thus, the GeV luminosity of cloud A is evaluated to be in the range of (3.1–7.6) × 10^{-7} photons cm^{-2} s^{-1}, *and it dominates, by more than 2 orders of magnitude, the GeV flux produced by the SNR itself*. Since the intrinsic SNR contribution can thus be neglected, the total expected hadronically generated gamma-ray luminosity is simply the same as that from cloud A:

$$F_{\rm tot}(E > 100\ {\rm MeV}) \sim F_{\rm cloud\ A}(E > 100\ {\rm MeV}) = (3.1\text{–}7.6) \times 10^{-7}\ {\rm photons\ cm^{-2}\ s^{-1}}. \quad (5)$$

That this predicted flux is fully consistent with the measured value, $(4.36 \pm 0.65) \times 10^{-7}$ photons cm^{-2} s^{-1} (Hartman et al. 1999), further supports the proposed nucleonic source of the detected gamma rays. Also, the fact that the EGRET source is coincident with the molecular cloud, and not the SNR itself, is fully in agreement with our calculation of the expected relative fluxes from these two sources. In addition, the spectral index of the GeV source, $\Gamma = -2.3 \pm 0.2$ (Hartman et al. 1999), is in tune with that expected from the hadronic interactions of a *source* CR population (Fields et al. 2001).

To be certain of a nucleonic source of the detected GeV flux from cloud A, however, it is crucial to eliminate the alternative, electromagnetic origin of the gamma rays. We show that the *nondetection* of cloud A in the radio band (Slane et al. 1999; Ellison et al. 2001) rules out the possibility that electrons are contributing significantly to the GeV luminosity *of the cloud*. At the high particle densities of cloud A, the contribution of the electron inverse Compton process to the GeV luminosity can be neglected in comparison with the electron bremsstrahlung process (e.g., De Jager & Mastichiadis 1997). However, the electron flux needed to explain the intensity of the measured GeV emission via electron bremsstrahlung in the cloud material would produce an enhanced radio emission by the synchrotron mechanism that far exceeds the measured values. The expected ratio of gamma-ray (>100 MeV) electron bremsstrahlung flux to the radio synchrotron flux may be expressed as

$$\frac{F(E > 100\ {\rm MeV})}{F(\nu)_{\rm Jy}} = \frac{4.3 \times 10^{-21}}{c(p)}\, n_{\rm cm^{-3}} \times B_{\mu\rm G}^{-(1+p)/2} \nu_{\rm Hz}^{(p-1)/2}\ {\rm Jy^{-1}\ cm^{-2}\ s^{-1}}, \quad (6)$$

where

$$c(p) = 10^{-5(1+p)}(3.2 \times 10^{15})^{(p-1)/2}(p-1)^2 a(p),$$

$a(p)$ is given in Longair (1994), and $p = 2.3$ is the spectral index of the electron population, $N_e(E) \sim E^{-2.3}$.

Then, using the physical parameters of cloud A, together with an assumed magnetic field of ~25 μG (a conservative estimate for molecular clouds [Crutcher, Troland, & Kazes 1987; Crutcher 1999]), we can calculate that the predicted radio luminosity at 843 MHz—*under the assumption of an electronic origin of the GeV flux*—would be ~40 Jy. Since this flux is about an order of magnitude larger than the *upper limit* derived from the nondetection of cloud A at this frequency (Slane et al. 1999), we conclude that no significant part of cloud A's GeV radiation could be due to electronic processes unless the magnetic field strength in the molecular cloud were as low as the interstellar medium value of ~5 μG. Furthermore, were the GeV flux of 3EG J1714−3857 of electronic origin, cloud A would outshine even the radio-brightest northwest rim of the remnant, which is found to be emitting at only 4 ± 1 Jy at 1.36 GHz (Ellison et al. 2001). There is, of course, a relativistic bremsstrahlung contribution from *secondary* electrons and positrons produced by the decay of *charged* pions ($\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$) that are also generated in the hadronic interactions, but this gamma-ray intensity is expected to be more than an order of magnitude lower than the $\pi^0 \rightarrow \gamma\gamma$ flux above 100 MeV (Berezinskii et al. 1990).

3. OTHER SOURCES IN THE FIELD

There are also two other SNRs projected within 3EG J1714−3857's 95% contours, CTB 37A and CTB 37B. However, since these SNRs are more distant (11.3 kpc), and because their maximum possible interacting cloud mass (Reynoso & Mangum 2000) is measured to be an order of magnitude less than cloud A's, their contribution to the GeV luminosity is less than 2×10^{-8} photons cm^{-2} s^{-1}, or less than 5% of the measured 3EG J1714−3857 flux.

The two pulsars within the 95% confidence location contours of this EGRET source, PSR J1715−3903 and J1713−3844 (Manchester et al. 2001),[4] can also be eliminated as the source of the bulk of the measured GeV flux. PSR J1713−3844 at (l, b) = (348.°10, +0.°21) is a long-period pulsar ($P = 1.60011$ s) whose spin-down luminosity is 2 orders of magnitude below that needed to account for 3EG J1714−3857. Although spinning faster, PSR J1715−3903 at (l, b) = (348.°10, −0.°32) is still not energetic enough to be responsible for 3EG J1714−3857: it has a period $P = 0.27848$ s, the dispersion measure indicates a distance of $d = 4.8$ kpc, and the observed period derivative of 37.688×10^{-15} implies a spin-down luminosity of $\dot{E} \sim 7 \times 10^{34}$ ergs s^{-1} for a standard neutron star moment of inertia $I = 10^{45}$ g cm^2. Thus, $\dot{E}/d^2 \sim 3 \times 10^{33}$ ergs s^{-1} kpc^{-2}, which is more than 2 orders of magnitude below the lowest value among

[4] See on-line catalog at http://wwwatnf.atnf.csiro.au/research/pulsar/pmsurv.

the confirmed gamma-ray pulsars[5] (Kaspi et al. 2000). We thus conclude that the pulsar J1715−39 is not responsible for the bulk of the GeV emission of 3EG J1713.7−3946. This conclusion is supported by the lack of any X-ray counterpart of PSR J1715−39 in the available archival X-ray databases.

Lastly, the EGRET source 3EG J1713.7−3946 is not coincident with any other candidate gamma-ray sources such as OB associations, Wolf-Rayet, or Of stars (Romero, Benaglia, & Torres 1999; Torres et al. 2001b). The analyses of both Tompkins (1999) and Torres et al. (2001c) also show this source to be nonvariable, as should be the case for an interacting SNR.

4. CONCLUSIONS

We have argued that the unidentified EGRET source 3EG J1714−3857 (Hartman et al. 1999) results predominantly from the gamma rays produced by nuclei accelerated by SNR RX J1713.7−3946 interacting with those resident in the dense and massive molecular cloud immediately abutting the remnant. A recent analysis of the *electronic* emissions of this remnant by Ellison et al. (2001) directly supports our proposal by suggesting that 25%–50% of the forward-shock kinetic energy is likely being taken up in accelerating ions to CR energies.

However, it should be noted that a number of theoretical assumptions are built into the simple models cited in our analysis of the hadronic gamma-ray production (Morfill et al. 1984; Aharonian et al. 1994; Drury et al. 1994; Aharonian & Atoyan 1996). For instance, the diffusion and confinement of the protons in the dense and magnetized media of molecular clouds are complicated problems whose detailed analysis is beyond the scope of this Letter (see, e.g., Zweibel & Shull 1982; Berezinskii et al. 1990; Dogiel & Sharov 1990; Chandran 2000). The large angular size of the EGRET error box (Fig. 1) also leaves open the possibility that some other, as yet unidentified, source could also be contributing significant gamma-ray flux. Observations of this region with the upcoming higher sensitivity and spatial resolution satellite-based GeV telescopes, such as *AGILE* and *GLAST*, will thus be very important. We also propose that cloud A of RX J1713.7−3946 be a high-priority target for CANGAROO-III and HESS, the forthcoming high-sensitivity ground-based TeV Cerenkov telescope arrays in the Southern Hemisphere. Such observations of very high energy photons from cloud A could directly probe the maximum proton energy, $E_{\text{p-max}}$, accelerated by RX J1713.7−3946 since the hadronic gamma-ray spectrum begins steepening at $E_\gamma \sim 0.1E_{\text{p-max}}$ and is cut off at $E_\gamma \sim E_{\text{p-max}}$ (e.g., Naito & Takahara 1994).

In conclusion, the facts that TeV energy CR electrons are accelerated in SNR RX J1713.7−3946 (Muraishi et al. 2000), that the abutting cloud material is inordinately excited, that the cloud region is of low radio and X-ray brightness, that the GeV luminosity is nonvariable and in quantitative agreement with that expected from π^0 gamma decays, that the spectral index is as expected for a hadronic CR source population, and, lastly, that there are no other known candidate sources within the 95% location contours of 3EG J1714−3857 capable of explaining the GeV flux all suggest that this EGRET source is the gamma-ray signature of accelerated nuclei from SNR RX J1713.7−3946 interacting with those of the neighboring dense and massive molecular cloud.

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[5] We do not consider PSR B1055−52 here since there is an open controversy regarding the distance to this pulsar (see Combi, Romero, & Azcarate 1997, Romero 1998, McLaughlin & Cordes 2000, and Torres, Butt, & Camilo 2001a for discussions).

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