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Gamma-ray Emission in GPS Quasars

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Abstract In this paper, it is argued that the relativistic jets in gigahertz peaked spectrum (GPS) quasars are oriented at small angle to the line of sight and are powerful gamma-ray sources. Besides luminous hard gamma-ray emission, most of them may have significant soft gamma-ray and X-ray emission due to infrared photons from very dense and dusty nuclear interstellar media in GPS quasars, which is consistent with *ASCA* X-ray observations. Because Compton cooling in GPS quasars is stronger than in flat spectrum radio quasars (FSRQs), synchrotron emission in GPS quasars may less dominate over thermal emission of the accretion disk and hot dust than in FSRQs, hence most GPS quasars show low optical polarization and small variability. We suggest that it is the significant radio emission of electron/positron pairs produced by the interaction of gamma-rays with the dense gas and dust grains in GPS quasars that makes GPS quasars show steep radio spectra, low radio polarization, and relatively faint VLBI/VLBA cores. The gamma-ray emission in GPS quasars can be tested by the observation of the *INTEGRAL* and *GLAST* in the near future.

Key words: galaxies: active — galaxies: jets — quasars: general — radiation mechanism: nonthermal — gamma-rays: theory — X-rays: galaxies

1 INTRODUCTION

The gigahertz peaked-spectrum (GPS) radio sources, including GPS galaxies and quasars (GPSQs), are compact (< 1 kpc) powerful radio sources with well-defined peaks in their radio spectra (see O'Dea 1998 for a review). GPS sources are a significant fraction of the bright radio source population (∼10%). Among the 66 GeV gamma-ray-detected AGNs (Aharonian et al. 2004; Bai & Lee 2001; Hartman et al. 1999; Mattox et al. 1997; Mukherjee et al. 1997; Thompson et al. 1995), three sources, CTA 102, PKS 0528+134, and PKS 1127 − 145, are GPSQs (O'Dea et al. 1991; Zhang et al. 1994; Stanghellini et al. 1998). Are other GPSQs possible gamma-ray sources?

Unlike blazars which have very bright cores and one-side jets on VLBI and VLBA images, most GPSQs have very faint cores and complex structures, with some showing counter-jet on VLBI and VLBA images (Stanghellini et al. 2001). About 30% of GPSQs even show two VLBI lobes (micro-lobes) on both sides ("compact doubles" or "compact symmetric objects", O'Dea

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1998). In addition, GPSQs are low-polarization quasars unlike typical blazars, and seem to have little variability (e.g., Stanghellini et al. 2001, 1998; O'Dea 1998). For these reasons, it is generally believed that the morphology and luminosities are not dominated by Doppler-boosted emission (O'Dea 1998) and that the relativistic jets in GPS sources are oriented at large angle to the line of sight (e.g., Stanghellini et al. 2001; Urry & Padovani 1995). It is suggested that some GPSQs (for example, the gamma-ray detected ones) are not real GPS sources but blazars, and should be eliminated from the GPS class (Lister 2003). However, all three gamma-ray detected GPSQs also have a low polarization, both PKS 1127 − 145 (Siemiginowska et al. 2002) and CTA 102 (Wehrle & Cohen 1989) have two bright components on VLBI and VLBA images, and PKS 0528+134 may even have a counter jet (Zhang et al. 1994). Why are they different from typical blazars in the radio band?

In this paper, we show evidence that the relativistic jets in GPSQs are oriented at small angle to the line of sight, and thus they could be powerful gamma-ray sources. $H_0 = 50 \mathrm{km\,s^{-1}Mpc^{-1}}$, and $q_0 = 0.5$ are assumed throughout this study.

2 MODEL ASSUMPTIONS

Jets are undoubtedly inhomogeneous, but blazar studies show that jet luminosity is dominated by a single electron population in a homogeneous emitting region, except for the low frequency emission in both synchrotron and inverse-Compton components. We calculate the SEDs in a homogeneous model, assuming that the emitting region is a homogeneous sphere with radius R embedded in a magnetic field B and moving with bulk Lorentz factor Γ, and that the viewing angle of the jet $\theta \sim 1/\Gamma$, so that the Doppler factor $\delta \sim \Gamma$.

For a continuous electron injection at a rate $Q(\gamma)$ [$\mathrm{cm^{-3}s^{-1}}$] (γ is the random Lorentz factor of electrons, $\gamma_{\rm min} < \gamma < \gamma_{\rm max}$), rapid cooling of high energy electron results in a break point $\gamma_{\rm br}$ in the function of electron distribution $N(\gamma)$. In the SED calculations, we assume $\gamma_{\rm min} = \gamma_{\rm br}$ and a power-law injection $Q(\gamma) = Q_0\gamma^{-2\alpha_2}$ (α_2 is the spectral index above the peak frequency), so that all injected high energy power converts to high frequency radiation, and $N(\gamma) = \tau(\gamma)\frac{Q(\gamma)}{2\alpha_2-1} = N_0\gamma^{-2\alpha_2-1}$, for $\gamma \geq \gamma_{\rm br}$. For $1 < \gamma < \gamma_{\rm br}$, we assume that $N(\gamma) = N_0\gamma_{\rm br}^{2\alpha_1-2\alpha_2}\gamma^{-2\alpha_1-1}$ (α_1 is the spectral index below the peak frequency). This form of electron distribution $N(\gamma)$ ($1 < \gamma < \gamma_{\rm max}$) could be the case in which electrons are re-accelerated. High energy electrons efficiently convert the injected energy to radiation while low energy electrons lose little of their energies before being re-accelerated, as if electrons were injected between $\gamma_{\rm br}$ and $\gamma_{\rm max}$.

The emissivity of synchrotron and inverse Compton emission, and the self-absorption of synchrotron are calculated with standard formula which can be found in text books and the literature. The Klein-Nishina effect is treated approximately as

$$\sigma = \begin{cases} \sigma_T & \text{for } \gamma x < 3/4\,, \\ 0 & \text{for } \gamma x > 3/4\,, \end{cases} \tag{1}$$

where x is the energy of the seed photon in units of rest mass energy of electron.

As generally treated, the external seed photon is assumed to be isotropic in the jet comoving frame, and is treated as a diluted blackbody emission with a mean energy $E_{\rm ext}$ ($h\nu_{\rm ext}$) and an energy density of $u_\nu = U_{\rm ext}u(T_c)$, where $U_{\rm ext}$ is the integrated energy density of external photon field, and $u(T_c)$ is the normalized energy density of black body at temperature $T_c = E_{\rm ext}/k$.

$$u(T_c) = \frac{2h\nu^3}{aT_c^4c^2}\frac{1}{\exp(h\nu/kT_c) - 1}\,, \tag{2}$$

where h, k, and a are constants of Plank, Boltzmann, and radiation density, respectively. In the SED calculations, we assume $E_{\rm ext} = 10$ eV for UV photons from the broad-line regions (BLR), and $E_{\rm ext} \sim 0.1$ eV ($T_{\rm dust} \sim 1000$ K, O'Dea 1998) for IR photons from the dust emission.

3 EVIDENCE ON DOPPLER BOOSTING IN GPSQS

The luminosity of line emission in GPSQs is similar to that in FSRQs (O'Dea 1998, and references there in), so the luminosity of accretion disk and the intrinsic jet power in GPSQs are roughly the same as those in FSRQs. If the relativistic jets in GPSQs have larger viewing angles than those in blazars, i.e., the jet emission in GPSQs is not beamed towards the Earth, GPSQs should be less luminous at X-rays than FSRQs. However, this is not the case. Though GPS sources usually show extra absorption in the soft X-ray band, *ROSAT* X-ray (0.1–2.4keV) observations show that 9 out of 13 GPSQs in O'Dea's complete sample of GPS sources have been detected, with a detection rate of 70%. O'Dea's complete sample of GPS sources was selected from 1-Jy radio catalog (1Jy at 5 GHz, Stickel, Meisenheimer & Kühr 1994). Among 214 FSRQs in 1Jy radio catalog, 124 of them were detected by *ROSAT*, with a detection rate of 57.9% which is even lower than that of GPSQs. This implies that the X-ray emission in GPSQs is relativistically beamed towards the Earth, as FSRQs do. That is to say, the relativistic jets in GPSQs could be oriented at small angle to the line of sight.

In fact, arguments that GPSQs are not dominated by Doppler boosted emission are merely based on radio observations. In some blazars the signature of the core can be occasionally hidden in its integrated radio spectrum (Lister 2003). Furthermore, the radio spectra of many blazars change dramatically with time, often showing remarkably GPS-like convex profiles during flux density outbursts (Kovalev et al. 2002). Some non-jet radio emission by $e^{\pm}$ pairs may cause these phenomena and make GPSQs different from FSRQs (see Discussion Section).

4 THE INVERSE-COMPTON EMISSION IN GPSQS

As stated above, the relativistic jets in GPSQs could be oriented at small angle to the line of sight, as in the cases of FSRQs. The luminosity of line emission in GPSQs is similar to that in FSRQs (O'Dea 1998, and references there in), so the luminosity of accretion disk, and the energy density of UV photons $U_{\rm UV}$ in GPSQs are approximately the same as that in FSRQs. GPSQs thus could be as luminous as FSRQs at gamma-rays.

Studies on the SED properties of blazars suggest that from high-frequency peaked BL Lac objects to low-frequency peaked ones to FSRQs, blazar SEDs show a remarkable continuity, and that while gamma-rays in BL Lac objects are likely produced via the SSC mechanism, in line-emission blazars – FSRQs, cooling is dominated by Comptonization UV photons reprocessed/reflected by BLR clouds, peaking power output at GeV gamma-ray energies (e.g., Sambruna 1997; Fossati et al. 1998; Kubo et al. 1998; Mukherjee et al. 1999; Hartman et al. 2001). Up-scattering IR photons, the same population of electrons in FSRQs could produce softer gamma-rays peaking at MeV energies (Sikora, Begelman, & Rees 1994; Blazejowski et al. 2000). Among GeV FSRQs, only five of them (PKS 0208−512, PKS 1622−297, 3C 279, 3C 454.3, and 3C 273) show gamma-ray spectra extending downward to MeV energies (Schönfelder et al. 2000; McNaron-Brown et al. 1995), indicating that in most FSRQs, $U_{\rm IR}$ is negligible compared to $U_{\rm UV}$.

There are several pieces of evidence suggesting that GPS sources contain very dense and dusty nuclear interstellar media (O'Dea 1998 and references therein; Siemiginowska 2003). Though the IR emission of the diffused dust and molecular gas may contribute less to the total IR luminosity than the dust torus, it may be the dominant IR photon field in the comoving frame of GPSQ jets owing to Doppler boosting which depends strongly on the viewing angle (the viewing angle of dust torus is much larger). It is possible that in most GPSQs, $U_{\rm IR}$ is not negligible or even larger than $U_{\rm UV}$ in some sources, because $U_{\rm UV}$ is roughly the same as that of FSRQs. Comptonization of IR photons are thus comparable to that of UV photons from BLR, or even dominant in some sources. That is to say, most GPSQs are not only luminous GeV gamma-ray sources, but may also have comparable MeV gamma-ray emission. This may

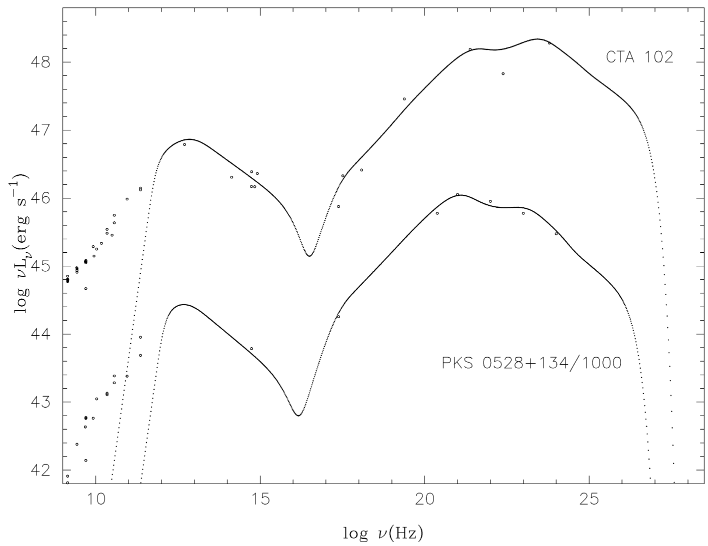

Fig. 1 SED fits of CTA 102 (top) and PKS 0528+134 (bottom) with homogeneous model taking into account the Comptonization of IR photons. The open circles are the observed spectra: For CTA 102, data are from NED, Fossati et al. 1998, and McNaron-Brown et al. 1995; For PKS 0528+134, multiplied by 0.001, X-ray and gamma-ray data are simultaneous (VP0.2-0.5), and radio to optical data are nonsimultaneous observations from NED and Fossati et al. 1998. Model parameters for CTA 102 are $R = 6.0 \times 10^{16}$ cm, $B = 1.5$ gauss, $\delta = 16$, the injected power of electrons $L_{\rm inj} = 2.8 \times 10^{44}\,{\rm erg\,s^{-1}}$, $\gamma_{\rm br} = 250$, and $\gamma_{\rm max} = 10000$. In the jet comoving frame, $U_{\rm UV} = 1.63\,{\rm erg\,cm^{-3}}$, and $U_{\rm IR} = 1.07\,{\rm erg\,cm^{-3}}$. For PKS 0528+134, $R = 6.0 \times 10^{16}$ cm, $B = 2.5$ gauss, $\delta = 15.5$, $L_{\rm inj} = 1.5 \times 10^{45}\,{\rm erg\,s^{-1}}$, $\gamma_{\rm br} = 160$, $\gamma_{\rm max} = 6000$, $U_{\rm UV} = 3.26\,{\rm erg\,cm^{-3}}$, and $U_{\rm IR} = 6.53\,{\rm erg\,cm^{-3}}$.

be the reason why CTA 102 and PKS 0528+134 are bright at both MeV and GeV energies (see Fig. 1). It is likely that the third GeV GPSQ, PKS 1127 − 145, is also a bright MeV gamma-ray source (see Fig. 2).

As can be seen in Figs. 1 and 2, strong Comptonization of IR photons makes a GPSQ not only a bright MeV gamma-ray source but also a powerful X-ray emitter, especially in hard X-rays. GPSQs are thus on average brighter at X-ray energies than FSRQs. This is consistent with *ASCA* X-ray observations. Among all 35 radio-loud quasars detected by *ASCA* (0.5–10keV, Reevs & Turner 2000), 6 of them are GPSQs. Except for 1614+051, other five of them (0237−233, 0528+134, 2000−330, 2126−158, and 2230+114) are in 1-Jy catalog. Considering the small ratio between the populations of GPSQs and FSRQs (e.g., $\sim 11:100$ in 1-Jy catalog), the detection rate of GPSQs by *ASCA* is much higher than that of FSRQs, suggesting that GPSQs are on average brighter than FSRQs in hard X-rays.

As mentioned above, the energy density of UV photons in GPSQs is roughly the same as that in FSRQs, so Compton cooling in GPSQs is on average stronger than that in FSRQs owing to extra Compton cooling of dense IR photons in GPSQs. Synchrotron emission in GPSQs is thus a smaller fraction of bolometric luminosity than it is in FSQRs. Synchrotron emission in GPSQs may less dominate over thermal emission of the accretion disk and hot dust than in FSRQs, or even be comparable to thermal emission during low states, showing low optical polarization and small variability, which are consistent with the observations (O'Dea 1998 and references therein).

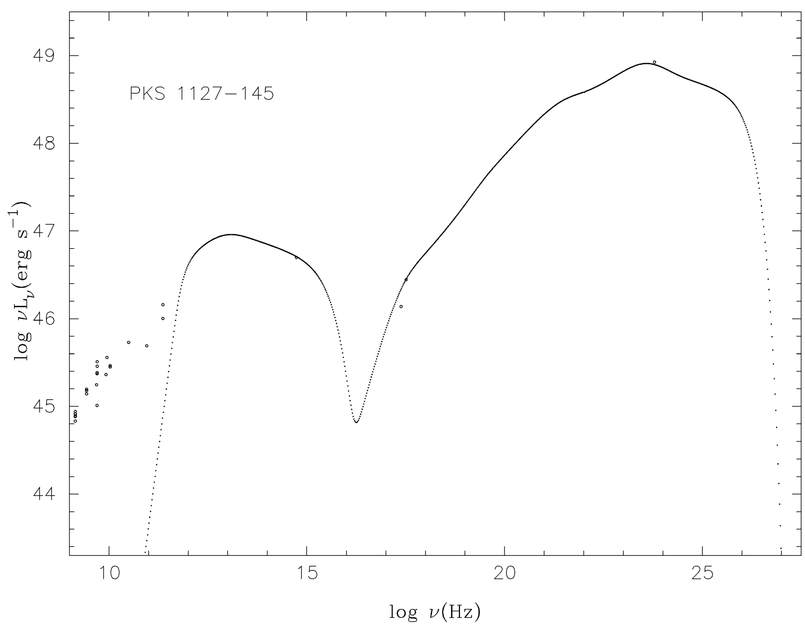

Fig. 2 Model fit to the SED of PKS 1127−145. The observed spectra (open circles) are from NED, and are nonsimultaneous. The model parameters are $R = 6.0 \times 10^{16}$ cm, $B = 2.5$ gauss, $\delta = 16.5$, $L_{\rm inj} = 7.5 \times 10^{44}$ erg s^{-1}, $\gamma_{\rm br} = 250$, and $\gamma_{\rm max} = 5000$. In the jet comoving frame, $U_{\rm UV} = 6.52$ erg cm^{-3}, and $U_{\rm IR} = 1.96$ erg cm^{-3}.

5 DISCUSSION AND CONCLUSIONS

In GPS sources there could be a very dense and dusty nuclear interstellar media (O'Dea 1998 and references therein; Siemiginowska 2003). The e$^{\pm}$ pair production by the interaction of gamma-rays with atoms and protons in dust grains and gas may be significant in GPSQs, though the cross section is only about $0.01\sigma_T$. The gamma-rays are beamed to the surrounding gas and dust grains, and the pairs are produced within the beam on both sides of the central engine. Suppose the gamma-ray optical depth to be $\sim$0.001 for a geometrical length of $\sim$ 100 pc (corresponding to a Thomson depth of $\sim$0.1), pairs on each side can get a power of $> 10^{44}$ erg s^{-1} (assuming $L_\gamma > 10^{47}$ erg s^{-1}).

The created pairs are relativistic particles with a energy of about a half of the gamma-ray energy ($\gamma < 1000$ for most pairs). The bulk motion of pairs is unlikely relativistic, so most pairs emit mainly via synchrotron in the radio band with steep spectra, forming two very bright jet "knots" or micro-lobes on two sides, and offer an extra contribution to radio luminosity, $> 10^{44}$ erg s^{-1} on each side of the core, which is comparable to or even large than the total radio power emitted by electrons in FSRQ compact jets (the VLA cores). This may be the reason why all GPSQs have relatively faint VLBI/VLBA cores, most GPSQs have low apparent jet speeds, and some GPSQs even show two-side radio structures (the jet has a relatively larger viewing angle), and the reason why all GPSQs have steep radio spectra, and show low radio polarization. The radio luminosity of pairs is proportional to the gamma-ray luminosity, hence is "indirectly" Doppler boosted. This may be the reason why GPSQs follow the same correlation between luminosities of radio and X-ray as FSRQs (Brinkmann, Yuan & Siebert 1997).

In conclusion, the relativistic jets in GPSQs could be oriented at small angle to the line of sight. GPSQs are thus possible powerful gamma-ray sources. Besides strong GeV gamma-ray emission, more than 50% GPSQs may have significant MeV gamma-ray emission due to strong Comptonization of IR photons. This can be tested by gamma-ray observation of the *INTEGRAL* and *GLAST* to be launched in the near future. The detection rate of GPSQs by *GLAST* should be similar to that of FSRQs.

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