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Q0906+6930: The Highest-Redshift Blazar

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ABSTRACT

We report the discovery of a radio-loud flat-spectrum QSO at z=5.47 with properties similar to those of the EGRET γ-ray blazars. This source is the brightest radio QSO at z>5, with a pc-scale radio jet and a black hole mass estimate $\gtrsim 10^{10} M_{\odot}$. It appears to be the most distant blazar discovered to date. High energy observations of this source can provide powerful probes of the background radiation in the early universe.

Subject headings: galaxies: jets – quasars: general

1. Introduction

AGN classification is still somewhat heuristic, but in the unified model, blazars are believed to be sources viewed close to the axis of a powerful relativistic jet (Urry & Padovani 1995, and references therein). They thus have compact flat spectrum radio counterparts, with apparent superluminal motion at VLBI scales. Optically, the sources are often variable, exhibit significant polarization and show either broad emission lines (flat spectrum radio quasar) or continuum-dominated (BL Lac) spectra. Perhaps the most interesting consequence of the jet/line-of-sight alignment is the observability of a Compton scattered component at X-ray to GeV or (for nearby sources) TeV energies. The interaction of the high energy jet particles and radiation with surrounding photon fields allows unique probes of the extragalactic background light (EBL).

One of the principal discoveries of the *EGRET* experiment on the *Compton Gamma Ray Observatory* was the large population of blazars emitting at GeV energies. These represented the largest identified population in the third *EGRET* (3EG) catalog; still many high latitude

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sources remained unidentified. We have developed a method to extend identifications to fainter radio flux levels (Sowards-Emmerd, Romani & Michelson 2003; Sowards-Emmerd, et al 2004), finding counterparts for 70% of the $|b| > 10^\circ$ sources. Follow-on observations show that most of these are previously unidentified blazars. Upcoming GeV γ-ray missions, especially *GLAST*, will have much higher sensitivity and are expected to detect several thousand blazars. This substantially exceeds the total number of blazars cataloged to date (Landt et al. 2001). Thus in preparation for this mission, we have selected radio (& X-ray) sources with properties like the *EGRET* blazars and are obtaining optical identifications and spectroscopy (Sowards-Emmerd, Romani & Michelson 2004, SRM04).

To prioritize the optical observations, we have also developed a method for estimating the probability that a given position has an excess of γ-ray photons in the *EGRET* survey observations, including the effect of strong variability. The radio blazar candidates selected above show, as a set, a clear excess of γ-ray flux over random sky positions (SRM04); individually, they are well below the 4σ criterion for inclusion in the 3EG catalog. For example, radio blazar candidates with $\geq$75% probability of γ-ray excess are found at $\sim 0.012/\circ^2$, and thus may represent 10-20% of the new sources detectable to *GLAST*. These are prime candidates for optical follow-up; we find that most are indeed flat spectrum radio quasars with redshifts 1-2.5. In this set Q0609+6930, however, has a very high redshift of 5.47. Observations described below support a blazar identification for this source; this would be the highest redshift blazar discovered to date.

2. The discovery of Q0906+6930

Our selection algorithm for finding *EGRET*-type blazars is 'trained' by the properties of EGRET blazars identified in the 3EG catalog. We start from compact 8.4GHz sources (from CLASS, Meyers et al. 2003 or from our own VLA snapshots) and identify flat/inverted spectrum sources using NVSS counterparts. Our selection algorithm also applies a weak weighting toward X-ray sources sources detected in the *ROSAT* All-Sky Survey (RASS), although many of the *EGRET* blazars are below the RASS survey threshold. This weighting scheme differs from other blazar surveys (eg. DXRBS, Landt et al. 2001) and gives a much higher correlation with the 3EG sources. We follow up with optical spectroscopy obtained with the Marcario Low Resolution Spectrograph (LRS; Hill et al. 1998) at the Hobby•Eberly telescope (HET; Ramsey et al. 1998), obtaining source classifications and redshifts.

Q0906+6930 has a strongly inverted spectrum $\alpha_{1.4/8.4} = -0.4$ ($S_\nu \propto \nu^\alpha$) with a CLASS-epoch flux of $S_{8.4} = 190$mJy. The radio position is 09:06:30.75 +69:30:30.8 (J2000.0). This source was cataloged as compact at the $\sim 0.1''$ scale, but the short CLASS snapshots provide only limited $\sim$ 1mJy sensitivity to flux on arcsecond scales. This source is just included in our 'sub-threshold' γ-ray target list, with a likelihood analysis of the γ-ray counts giving a 75% probability for emission in excess of background at this position.

2.1. HET/LRS optical spectrum

We obtained 2×300s exposure with the HET LRS on 1/18/04, under poor $\sim 2''$ conditions, which nonetheless showed a classic Lyα forest-absorbed QSO spectrum with high $z \approx 5.5$ redshift. Follow-on exposures of 2×600s on 1/27/04 with a 300l/mm grating, $2''$ slit and 5150Å long-pass filter (to preclude 2nd order contamination) and improved $\sim 1''$ seeing produced the spectrum shown in figure 1. These data were subject to optimal extraction, calibration and telluric correction using standard IRAF routines. Uncorrectable fringing and imperfect sky subtraction introduce large noise beyond 9500Å. The resulting spectrum has a dispersion of 4Å /pixel and an effective resolution of 16Å , covering $\lambda\lambda$5200-10,000Å.

In the spectrum Lyα is strong, but absorbed; we estimate a pre-absorption rest equivalent width of 50-60Å. The redshift, z=5.47±0.02, is best constrained by the NV and OIV lines; the OIV rest EW is 22Å and the kinematic width is $W_{FWHM} = 5,000 \pm$ 500km/s. The UV continuum luminosity at 1350Å is $\lambda \mathrm{L}_{1350} \approx 5 \times 10^{47}$erg/s (we use $H_0 = 71$km/s/Mpc, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$). CIV is not clearly detected, so if we use the OIV kinematic width in the Vestergaard (2002) UV M-L relationship we obtain $\mathrm{Log}M = 6.2 + \mathrm{Log}[(\mathrm{W_{FWHM}}/10^3\mathrm{km/s})^2(\lambda L_{1350}/10^{44}\mathrm{erg/s})^{0.7}] \approx 10.2$. This is near the upper end of masses inferred for high z sources and formation of such a high M black hole after $\sim$ 1Gyr is difficult to understand. There are several candidate CIV absorption line systems redward of Lyα. Two candidate systems with apparent damped Ly lines are marked. The presence of intervening absorption raises the possibility that Q0906+6930 is lensed, which could inflate our estimate of the BH mass. However, CLASS finds no radio lens, there is no extended emission visible on the POSS and the source appears point-like in a short pre-spectrum acquisition image. Improved optical/near IR spectroscopy is needed to tighten up the mass estimate, and to improve the identification of the absorption systems as strong CIV doublets.

2.2. VLBA Observations and Source SED

To search for evidence of compact jet structure that would support the blazar designation of Q0906+6930, we obtained snapshots with the VLBA at 2cm and 7mm wavelengths

(Figure 2). With 10 stations, we obtained an average of 60 minutes of on-source per baseline under nominal observing conditions on 2004 February 27 (MJD 53062), recording two 8-MHz bandpasses at 15.36 GHz. We used 0716+714 to calibrate phases and delays prior to self-calibration of the blazar, using AIPS. We constructed deconvolved images with natural weighting of the data (half-power beam width 1.55×0.47mas at -2°). The RMS background noise in the image was $\sim 10\%$ above the thermal noise limit of 0.18 mJy. The 7 mm observations recorded ~ 41 minutes on-source per baseline on 2004 March 3 (MJD 53067), tuned to 43.21 GHz. About 30% of the data could not be self-calibrated because of rapid ($\ll 1$ minute) tropospheric fluctuations. In addition, we obtained no usable data from the Los Alamos antenna, due to weather, and from one polarization-baseband combination recorded at the Saint Croix antenna. The half-power beamwidth was 0.55×0.30 mas at $-3.7°$ for natural weighting.

The compact core was unresolved at both wavelengths. In the 2cm image a clear jet component is seen at PA 225±1°. For a two component Gaussian model we fit a core flux of 115±0.3mJy and a jet flux of 6.3±0.4mJy. The jet is marginally detected in our 7mm image with a maximum $\lesssim 0.2$ beams from the position of the 2cm peak, although it is only comparable to the largest peaks in the image background. The two component fit gives a core flux 42±1.9mJy and jet flux 4.1 ± 1.1mJy, for a 3.7σ detection.

Our combined EGRET likelihood analysis finds a nominal $\sim 1.5\sigma$ excess of γ-ray photons at the radio position. In the viewing period with the most significant detection, VP0220, the source produced $1.12 \pm 0.76 \times 10^{-7} \gamma/\mathrm{cm}^2/\mathrm{s}$ (E>100 MeV). However, if other sources beyond the standard 4σ 3EG sources are present in this region the fit flux is even lower. At this point it is best to employ the mission-averaged upper limit $4 \times 10^{-8} \gamma/\mathrm{cm}^2/\mathrm{s}$ (E>100 MeV).

We can collect the existing data into a crude spectral energy distribution (SED, Figure 3). Comparing to the well known blazar 3C279 placed at z=5.47, Q0906+6930 has a brighter UV flux, fainter cm wavelength emission and (potentially) a GeV peak power nearly 10× greater. The source has by far the highest radio loudness $R = f_{5GHz}/f_{0.44\mu}|_{rest} \approx 10^3$ of any $z > 5$ QSO. We also guide the eye with a simple synchrotron-Compton spectrum (Krawczynski et al. 2004) for a broken power-law approximating a cooled electron spectrum. The synchrotron component is broadly similar to that of 3C279. The compact core spectrum (inset) appears to turn over at cm wavelengths and does not connect to the falling optical spectrum. This is not however unexpected, as most blazars show extra radio components at cm wavelengths. If the 7mm jet detection is trusted, the $\alpha_{2cm/7mm} \approx 0.6$ of the jet component is somewhat flatter than that of the core $\alpha \approx 0.9$. This is unusual, although not unique for pc-scale jets (A. Marscher, private comm.); additional VLBI observations will be needed to see if this is temporary due to jet component brightening at 7mm. With only a marginal

GeV detection and an X-ray upper limit, the amplitude of the Compton component is poorly constrained. However, it is interesting to note that the broad line region flux is much larger than that of 3C279 with with a $2-3\times$ brighter optical continuum and rest equivalent line widths $10\times$ larger. Since comptonized BLR flux is generally believed to dominate the GeV emission, a bright γ-ray peak may be motivated, as shown by the dotted curves.

3. Prospects for High Energy Detection

We expect the Compton scattered emission of blazar jets to be highly beamed. Thus, few blazar X- and γ-ray sources are visible, but these may appear quite bright. The GLAST mission will have a large duty cycle and a survey sensitivity $\sim 2\times10^{-9}\gamma/\mathrm{cm}^2/\mathrm{s} \approx 10^{-12}\mathrm{erg}/\mathrm{cm}^2/\mathrm{s}$ (E>100 MeV), so even if the source is a flaring 3C279 analog, the prospects for detection are good. If the GeV spectrum of this source can be measured, then GLAST can observe the effect of pair attenuation of the >GeV flux on the optical-IR EBL (Madau & Phinney 1996). At its high redshift $\leq$10 GeV observations of Q0906+6930 will be probing $\leq 3\mu$ photons from high z star formation. This EBL is presently poorly understood, but an approximate attenuation curve based on the lower z EBL is applied for the combined spectrum (full line). The cut-off is well within the GLAST range. It may be measured if, for example, a stable absorption cutoff is seen on a GeV spectrum whose slope and amplitude varies with time.

In the X-ray regime, core emission probes the low energy Compton component, with the best connection to the radio. However, most interesting is the possibility of detecting a resolved $\sim 1''$ ($\sim$ 10kpc) scale X-ray jet produced by Compton up-scatter of CMB photons. Such extended ($\sim 2''$) jet structure has been seen in *CXO* observations of the QSO GB 1508+5714 (Siemiginowska et al 2003) at z=4.3. This feature is also seen as a faint radio jet (Cheung 2004) and the $\sim 10^2 f_X/f_R$ ratio supports the CMB up-scatter hypothesis. Extended emission X-ray observed $\sim$20$''$ from the $z = 5.99$ QSO J1306+0356 (Schwartz 2002b) may represent a second high-z jet, although radio emission is not seen. With a $(1+z)^4$ increase in the energy density of the CMB seed photons, such jets may be detectable to very high redshifts(Schwartz 2002a). Q0906+6930 at z=5.47 experiences $1752\times$ the local CMB energy density. As we already have evidence for an energetic jet, prospects for detection of a Compton up-scatter component are good and we are pursuing the required X-ray and radio observations to test this hypothesis. If seen, the link to the external seed field gives X-ray/radio measurements unique power to probe the particle and field populations in this high-z jet.

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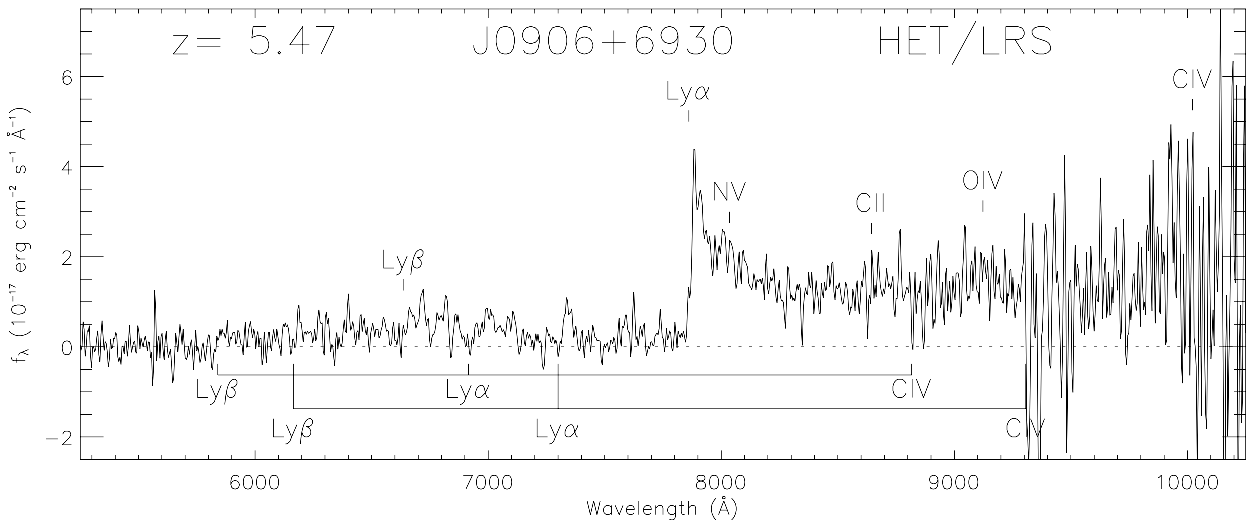

Fig. 1.— HET/LRS spectrum of Q0906+6930.

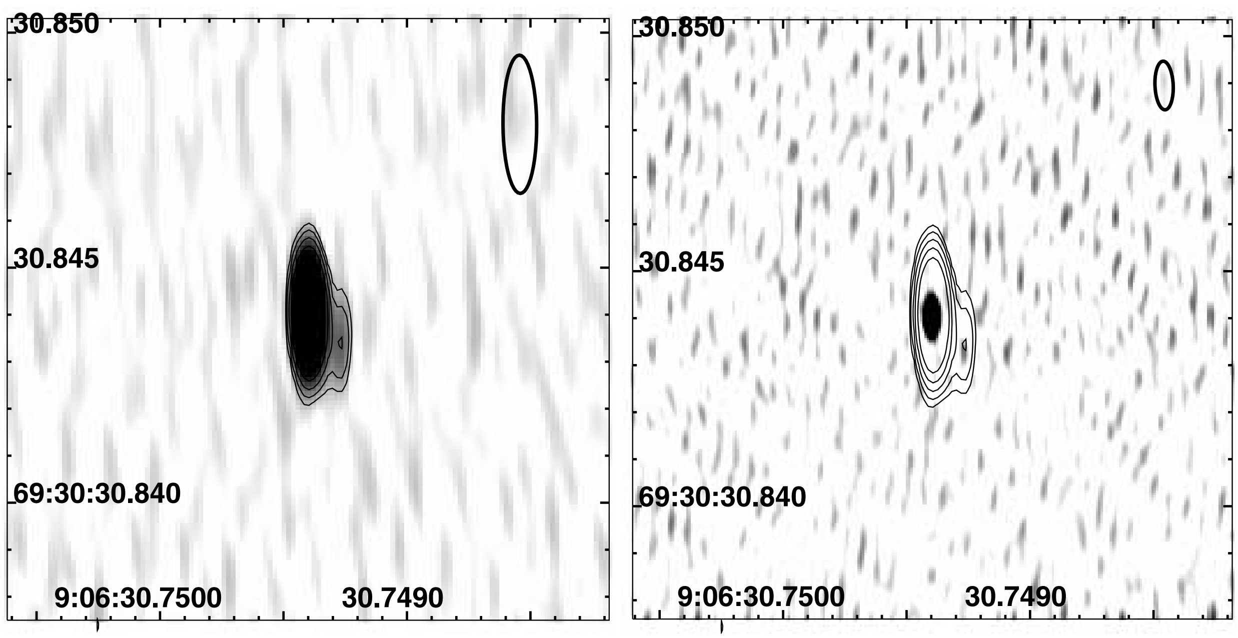

Fig. 2.— VLBA snapshot images of Q0906+6930. Left – Emission at 2cm wavelength, with a peak flux of 115mJy/beam and contours at (2^nmJy/beam, n=0,1,..). A jet shows clearly at PA=225°. Right – Emission at 7mm (grayscale with a hard stretch) and contours from the 2cm image overlayed. The jet appears marginally detected at the $\sim 3\sigma$ level. The convolving beams are shown (upper right) in each panel.

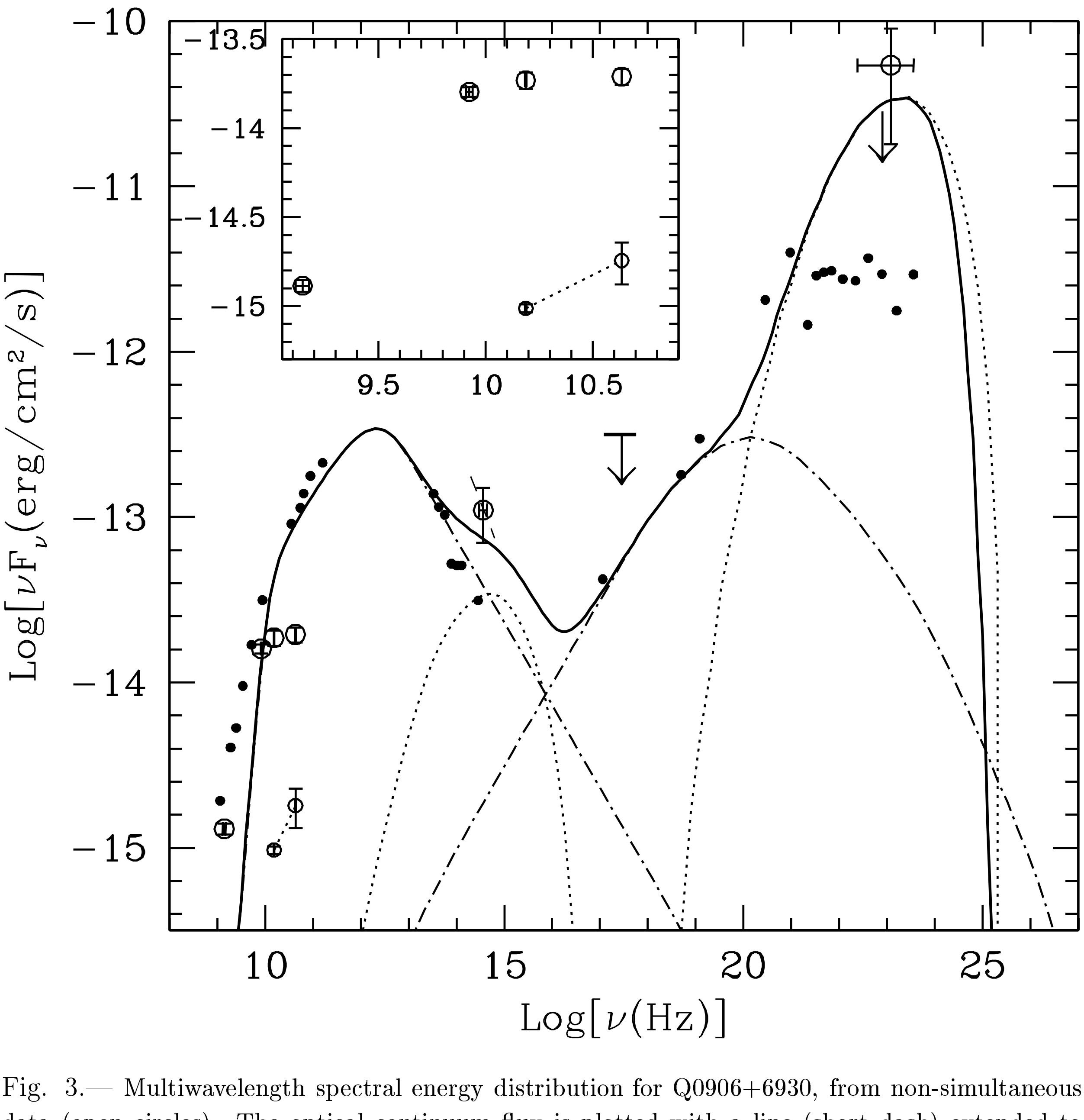

Fig. 3.— Multiwavelength spectral energy distribution for Q0906+6930, from non-simultaneous data (open circles). The optical continuum flux is plotted with a line (short dash) extended to show the slope. The X-ray upper limit is from the RASS. For the EGRET band we show the brightest epoch flux and the mission- averaged upper limit. For comparison we plot the SED of 3C 279 (points) Hartman et al. (2001), shifted to z=5.47. A Comptonized spectrum (synchrotron self-Compton, dot-dash line; broad-line region + Compton, dotted line) is plotted to guide the eye. The combined spectrum (solid line) includes the effects of EBL absorption.