An Investigation of Gravitational Lensing in the Southern BL Lac PKS 0537-441

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ABSTRACT

The BL–Lac family of active galaxies possess almost featureless spectra and exhibit rapid variability over their entire spectral range. A number of models have been developed to explain these extreme properties, several of which have invoked the action of microlensing by sub–stellar mass objects in a foreground galaxy; this not only introduces variability, but also amplifies an otherwise normal quasar source. Here we present recent spectroscopy and photometry of the southern BL Lac PKS 0537-441; with an inferred redshift of $z \sim 0.9$ it represents one of the most distant and most luminous members of the BL Lac family. The goal of the observations was not only to confirm the redshift of PKS 0537-441, but also to determine the redshift of a putative galaxy along the line of sight to the BL–Lac; it has been proposed that this galaxy is the host of microlensing stars that account for PKS 0537-441’s extreme properties. While several observations have failed to detect any extended emission in PKS 0537-441, the HST imaging data presented here indicate the presence of a galactic component, although we fail to identify any absorption features that reveal the redshift of the emission. It is also noted that PKS 0537-441 is accompanied by several small, but extended companions, located a few arcseconds from the point–like BL–Lac source. Two possibilities present themselves; either they represent true companions of PKS 0537–441, or are themselves gravitationally lensed images of more distant sources.

Subject headings: Quasars:Individual PKS 0537-441, Spectroscopy, Imaging, Gravitational Lensing
1. Introduction

BL–Lac systems represent an extreme class of active galaxy that exhibit featureless continua and undergo rapid variability at all wavelengths (c.f. Urry et al. 1997). A variety of models have been proposed to explain this extreme behavior, including both intrinsic processes such as relativistic jet accelerations (Georganopoulos & Marscher 1998) and external effects such as interstellar scintillation (Wagner & Witzel 1995). Another popular model proposes that BL–Lacs are in fact Optically Violent Variable (OVV) quasars whose continua have been amplified by microlenses in a foreground galaxy (Ostriker & Vietri 1985); here enhanced continuum swamps the quasar emission lines, resulting in the featureless spectrum which characterizes BL–Lacs. However, while this model explains the spectral characteristics of BL–Lacs the source of the variability is still considered to be intrinsic to the OVV source. More recent variants of this model propose the microlensed source is a relativistic jet, leading to extremely rapid variability (Gopal-Krishna & Subramanian 1991), while Nottale (1986) developed a microlensing model utilizing very low mass stars to account for both the variability and spectral properties of BL–Lac systems.

Although problems exist with this microlensing hypothesis (Kayser 1988; Gear 1991; Lewis & Williams 1997), observationally a number of BL–Lac systems appear to be superimposed on extended nebulosities (Stickel et al. 1988). While it is obvious that in several of these the nebulosity and the BL–Lac source are physically associated, in others the extended emission appears to be a foreground galaxy, distinct from the BL–Lac source (Stocke et al. 1985), bolstering the case for the microlensing of BL–Lacs. For microlensing to be effective at introducing rapid variability, a substantial optical depth of stellar objects is required and the BL–Lac source must possess a small impact parameter with respect to the foreground galaxy. With this, however, macrolensing effects become important and most BL-Lacs should appear offset from the core of any foreground lensing galaxy. In a fraction of systems, the impact parameter should be sufficiently small that the source will lie within the multiple imaging region of the lens, leading to several images of the same BL–Lac source about the core of the galaxy (Narayan & Schneider 1990). Observational studies reveal BL–Lacs to be well-centered upon their hosts (Abraham et al. 1991) and it has been proposed that the redshift of several BL–Lac systems have been mis-identified (Narayan & Schneider 1990); given the generally featureless spectrum exhibited by BL–Lacs such a conclusion is very likely.

The purpose of this paper is to explore a particular bright, distant BL–Lac system, PKS 0537–441, with the aim of understanding the role of microlensing in explaining its observed properties with a confirmation of its redshift, as well as determining the redshift of the putative galaxy along the line-of-sight. The layout
of the paper is as follows; Section 2 details the previous observations of PKS 0537–441 and the historical development of the microlensing model. New observations of PKS 0537–441 are discussed in Section 3, detailing both the NTT spectroscopy and HST imaging presented in this paper. In Section 4 the conclusions of this study are presented.

2. PKS 0537–441

Selected as a quasi-stellar source in the Parkes 2700MHz radio source (Peterson et al. 1976), PKS 0537–441 is seen to be a bright (\(B \sim 15\)) point–like source. A search for PKS 0537–441 on the Harvard Observatory photographic plate collection (Liller 1974) allowed the determination of a light curve of almost a century in extent, revealing long–term variations of \(\sim 5\) mag with fluctuations of \(\sim 2\) mag occurring over less than two months. While BL–Lac systems normally exhibit featureless spectra, weak emission lines are sometimes seen during quiescent periods. This was found to be the case for PKS 0537–441 which was observed to possess a prominent emission feature at 5304\(\AA\); it was proposed that this line is Mg II \(\lambda 2798\), placing BL–Lac at \(z = 0.894\) (Peterson et al. 1976; Stickel, Fried & Kuehr 1993). At this redshift the inferred properties of PKS 0537–441 places it amongst the most luminous of blazars. It was also suggested that C III\(\lambda 1909\) was also seen in these early spectra, although this has not been confirmed in subsequent observations.

Imaging by Stickel et al. (1988) revealed that PKS 0537–441 lies superimposed within a system of low redshift galaxies. One of these, a spiral galaxy at \(z = 0.186\), is seen 11" eastward, while PKS 0537–441 was inferred to lie at the core of a galaxy with an extended exponential disk profile. However, deeper follow-up exposures in the optical and NIR with the NTT and ESO 2.2m telescope failed to detect any extended emission around PKS 0537–441 (Falomo et al. 1992; Kotilainen et al. 1998), suggesting that the findings of Stickel et al. (1988) were erroneous.

Given its apparent brightness, PKS 0537–441 is an excellent target for studying the properties of BL–Lac objects and it has therefore been the subject of several monitoring campaigns at various wave-bands. Recently it was the subject of a monitoring campaign over a two week period at radio wavelengths (Romero et al. 1994), which revealed large variations, up to a factor of \(\sim 1.7\) on time-scales as short as \(\sim 10^4\) secs. Romero et al. (1995) interpreted these as being due to microlensing of a relativistic shock–front by stars in the putative foreground galaxy. The duration of the events \(\lesssim 1.2\) hours implies that, if the variability is microlensing-induced, the lenses must consist of sub-solar mass stars in the range \(\sim 10^{-4} - 10^{-3}M_\odot\).
3. Observations of PKS 0537–441

3.1. Spectroscopy

3.1.1. Observations

The spectroscopic observations were obtained on the red arm of the EMMI instrument at the NTT, operating in service mode. Six exposures, of total duration 6600 sec (3 × 1000 sec and 3 × 1200 sec), were obtained by observatory staff on Nov 8, 1997, and Jan 3 and 5, 1998. Taken with the Tek2k CCD (24µm pixels) and grism #4, the spectra cover the wavelength range 5800–11000 Å at 2.8 Å/pixel resolution. The gain was set to 1.1 e−/ADU, giving a read-noise of 4.2e− RMS, and the spectrograph slit was oriented North-South. The seeing at the time of the observations, determined from stellar profiles seeing in short pointing images, was better than 1″ for all the exposures.

Though the grism is reasonably efficient over the wavelength range covered by our spectra (more than 60% efficient redward of 7000 Å, but dropping to 25% at 5800 Å), the system response drops rapidly at the red end of our spectral range due to the rapid drop in the quantum efficiency of the CCD (∼ 8% efficient at 10000 Å).

3.1.2. Processing

The spectra were pre-processed in the usual fashion (debiasing, flat-fielding). So as to establish whether any extended emission could be seen in the spectra, for each exposure, we extracted the spectrum perpendicular to the dispersion direction in four bands of width 1″, 2″, 4″, and 6″. Sky-emission features were subtracted at this stage using the observed sky spectrum 10″ away from the blazar as a template. These spectra were then wavelength calibrated and observations of the standard star LTT2415 were used to remove the telluric features and flux-calibrate the spectra.

3.1.3. Results

Figure presents the co-added spectrum (with the corresponding noise spectrum) in the 1″ extracted band. The flux in the 6″ extracted spectrum is a factor of ∼ 6 times lower than that presented by Stickel et al. (1988), indicating that PKS 0537–441 was in a quiescent state. Our spectrum is also flatter, with a
slope of $\alpha = -1.3$ ($F_\nu \propto \nu^\alpha$), in contrast to -1.6 seen by Stickel 	extit{et al.} (1988). This low state of activity in the BL–Lac proved to be very fortuitous for this project as a number of emission features are visible including: $\text{[Ne V]}\lambda 3426$, $\text{[O II]}\lambda 3727$, $\text{[Ne III]}\lambda 3869+$He I$\lambda 3889$, $\text{[Ne III]}\lambda 3968$, $\text{[S II]}\lambda 4068/4076+\text{H}_\delta\lambda 4102$, $\text{H}_\gamma\lambda 4340+\text{[O III]}\lambda 4363$, $\text{H}_\beta\lambda 4861$ & $\text{[O III]}\lambda 4959/5007$ (c.f. Francis 	extit{et al.} 1991). Combining the centroid positions of these lines, we determine that the redshift of the BL–Lac source in PKS 0537–441 is $z = 0.892 \pm 0.001$, which confirms earlier measurements.

However, note that no absorption features indicative of the presence of an additional galaxy spectrum are present. In particular, we find no evidence for the MgI $\lambda 5200$ absorption complex, at least blueward of $\sim 9200\text{Å}$. Between $\sim 9200\text{Å}$ and $\sim 9700\text{Å}$, the spectrum is significantly affected by spurious residuals from the correction for telluric absorption, so the spectrum is not reliable. At the redshift of the blazar the MgI complex would lie at $9850\text{Å}$, but again no obvious absorption feature can be identified in Figure 1.

To further search for any evidence of an absorption system the spectra from the different width bands were subtracted; as the emission from any galaxy component will be extended, compared to the point-like emission from the quasar source, we would expect that the residual of the subtraction between bands of different width would help to remove the emission from the BL–Lac in PKS 0537–441, leaving proportionally more light from the foreground galaxy. In Figure 3, we present the difference between the spectra extracted from the $6''$ and the $4''$ bands; given the better than $1''$ seeing during these observations, virtually all of the point-like emission from the BL–Lac source should be contained within the $4''$ band. Close examination of this residual spectrum, however, also reveals a number of the emission features identified in Figure 1, and, given the broad width of the $H_\beta$ emission, these appear to be due to the BL–Lac source rather than being galactic in origin. As with Figure 1, no significant absorption features indicative of a normal galaxy spectrum are visible in Figure 2, making it impossible to determine the redshift of the extended emission, if present.

3.2. HST Observations

Is there any indication of the presence of a galaxy in the PKS 0537–441 system? As discussed in Section 3, the existence of a galaxy component in this system has a checkered history, originally detected in the imaging work of Stickel 	extit{et al.} (1988), with later studies failing to identify any extended emission (Falomo 	extit{et al.} 1992; Kotilainen 	extit{et al.} 1998). To address this question, high resolution images of PKS 0537–441 are required. Such observations were taken on the 29th of March 1996 with the Planetary
Camera chip of the WFPC2 instrument on board the Hubble Space Telescope, as part of a larger survey of BL Lac hosts (Urry et al. 1997; Urry et al. 1999). Four exposures, of duration 14 sec, 80 sec, and $2 \times 260$ sec, all in the F702W filter (a 585Å wide passband centered on 6913Å), were obtained from the HST archive.

### 3.2.1. Data Reduction

A median-combined image of the PC frames is presented in the left-hand panel of Figure 3; the BL–Lac appears point-like in this image and the companion galaxy, at $z = 0.186$ is clearly visible to the east of this source (c.f. Stickel et al. 1988). Three other ‘images’ are noted; two of these, marked A1 and A2 have been noted in other imaging campaigns (Stickel et al. 1988; Falomo et al. 1992), while B1 is noted here for the first time. The nature of these sources will be discussed in more detail in Section 4.

To search for extended emission beneath PKS 0537–441, a point-source profile fit and subtracted from the observed BL–Lac profile. For this, the point-spread function was modeled using the Tiny-Tim algorithm of Krist (1995). The subtracted image is presented in the right-panel of Figure 3. Examination of this panel does suggest that there is faint, non-axisymmetric extended emission around the BL–Lac source in PKS 0537–441.

To investigate this extended emission further, the radial profiles of both PKS 0537–441 and the companion galaxy (G1) where determined and are plotted together with the Tiny-Tim point-spread function in Figure 4. In the inner regions ($\lesssim 1''$), PKS 0537–441 is extremely well fit by the modeled point-spread function. At $1''2$, however, PKS 0537–441 begins to deviate from this model, with excess flux clearly seen at larger radii, at a level very similar to that of the companion galaxy (G1); this is the conclusion reached by Stickel et al. (1988). But again, is this extended emission real? Is the Tiny-Tim model adequate in describing the point-spread function in these Planetary Camera frames?

We note that the surface brightness profile presented by Falomo et al. (1992), from NTT images, is similarly well described in the central regions by a stellar point-spread function. However, their Figure 4 shows that there is a systematic enhancement of the surface brightness profile with respect to the point-spread function, at radii beyond $\sim 2''$. Though they concluded that this excess was not significant, due to their larger photometric uncertainties, this same discrepancy is seen to begin at the same radius in our Figure 4 derived from the ten times higher spatial resolution HST data. This consistency between our
experiment, and that of Falomo et al. (1992), indicates that it is likely that we are detecting a galactic component in the PKS 0537–441 system [this conclusion was also reached by Stickel Fried & Kuehr (1993)].

4. Conclusions

In this paper we have presented both spectroscopy and imaging of PKS 0537–441; this BL–Lac source is seen to possess extreme brightness and violent variability and it has been suggested that it is being microlensed by stars in a foreground galaxy. The apparent detection of such a system added weight to this suggestion (Stickel et al. 1988), although more recent observations have cast doubt on that claim (Falomo et al. 1992; Kotilainen et al. 1998). The microlensing hypothesis, however, does suffer from several drawbacks and has led to the suggestion that the redshift of PKS 0537–441 was misidentified (Narayan & Schneider 1990); given the typically featureless spectrum exhibited by BL–Lac objects such a conclusion is entirely reasonable. The observations presented here appear to have fortuitously caught PKS 0537–441 at a low point in its variability and several prominent emission features arising in the BL–Lac are apparent in the NTT spectra. These confirm PKS 0537–441’s redshift to be \( z = 0.892 \pm 0.001 \). At this redshift, PKS 0537–441 possesses an \( M_B \sim -28.5 \) (\( \Omega_o = 1 \& h = 0.5 \)), placing it amongst the most luminous of quasars.

An examination of these spectra failed to reveal any absorption signature indicative of the putative foreground galaxy supposedly responsible for microlensing the BL–Lac source. While several recent observations have failed to identify any signature of such a galaxy, the HST/WFPC2 imaging presented here apparently supports the existence of extended emission around PKS 0537–441. Given the problems of the microlensing model in explaining the properties of PKS 0537–441, we speculate that this extended emission arises in the host of the BL–Lac, rather than in some intervening galaxy. The reality and nature of the extended emission can only be investigated with further observations.

Does gravitational lensing significantly influence our view of PKS 0537–441? With the lack of any significant lensing mass along the line of sight the answer must be no, and considering that the \( z = 0.186 \) galaxy \( \sim 11'' \) from the BL–Lac can induce a gravitational lensing amplification of only a few percent, PKS 0537–441 must be appreciated for what it is, a luminous and highly variable member of the active galaxy family.

As pointed out in Section 3.2.1, an examination of the environment of PKS 0537–441 reveals the
presence of several small, but extended objects; two of these (A1 & A2) are also apparent in previous images, including those of Stickel et al. (1988). Such multiple components are seen in another bright, high redshift BL–Lac, AO 0235+164 (z ≈ 0.94); redshift measurements have determined that these systems are foreground to the BL–Lac source and represent a group of galaxies which appear to be responsible for gravitationally lensing AO 0235+164 (Stickel et al. 1998a). What is the nature of the systems near PKS 0537–441? Given their small, sub-arcsecond scale, they are most likely not members of a group of massive galaxies along the line of sight, as in AO 0235+164. Two possibilities do, however, present themselves:

- **Environment:** These systems may represent true companions of the BL–Lac source. At z = 0.892, 1″ ≈ 8 kpc (Ω_o = 1 & h = 0.5), and these galaxies would be ≈ 1 kpc in extent and be separated from the AGN by ≈ 32 kpc, suggesting that they could be dwarf satellites of PKS 0537–441.

- **Gravitational Lensing:** Could PKS 0537–441 be gravitationally lensing more distant sources? The additional components are very similar in both morphology and scale to several recently identified gravitationally lensed images of high redshift sources identified with the HST (c.f. Ratnatunga et al. 1999). Considering the separation of the various components from the BL–Lac and adopting a simple isothermal mass model to describe the gravitational lensing, the one-dimensional velocity dispersion of this potential would be 550 km s^{-1}, suggesting that PKS 0537–441 resides in a group/small cluster environment (Mortlock, Webster & Hewett 1996). Again, further observations would be required to confirm this hypothesis, but gravitational lensing may still play a role in our view of the PKS 0537–441 system.
REFERENCES


Fig. 1.— The co-added spectrum of PKS 0537–441 from the central 1″ of the NTT observations. Several emission features are visible including: [Ne V]λ3426, [O II]λ3727, [Ne III]λ3869+He Iλ3889, [Ne III]λ3968, [S II]λ4068/4076+Hγλ4102, Hβλ4340+[O III]λλ4363, Hβλ4861 & [O III]λλ4959/5007. Beyond 9000 Å the spectrum is affected by spurious effects from the correction of the telluric absorption features. The noise spectrum is also presented.

Fig. 2.— The residual between the spectrum of PKS 0537–441 extracted in 6″ and 4″ bands. Again, no significant absorption features indicative of a normal galaxy are apparent. The emission features are probably due to the BL–Lac source. The noise spectrum is also presented.
Fig. 3.— The left-hand panel presents the “raw” HST image of PKS 0537–441, obtained with WFPC2. PKS 0537–441 appears very point-like. The companion at z=0.186 is clearly visible (G1), as well as additional emission in the vicinity of the BL–Lac source (A1, A2, & B1). The right-hand panel presents the same image with a modified contrast level and with the BL–Lac emission subtracted via the modeling of the WFPC2 point spread function; beyond the inner 1′′, some very faint extended emission can be seen around PKS 0537–441.

Fig. 4.— The radial profile of PKS 0537–441 (dots) and the galaxy G1 (stars) as determined from the WFPC2 image. The point-spread function (line) was modeled using the Tiny-Tim algorithm of Krist (1995).