The Redshift of BL Lacertae Objects from High Signal-to-Noise VLT Spectra

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BL Lacertae objects are active galactic nuclei dominated by non-thermal continuum emission and characterised by absence or extreme weakness of emission lines. These properties in several cases hinder the determination of their distance and thus the assessment of the properties of the class. High signal-to-noise optical spectra of these sources obtained with the VLT help to overcome these difficulties and allow one to obtain new redshifts and set stringent limits on the distance for pure lineless objects.

The class of BL Lac objects

The absence or weakness of emission lines in the optical spectra is one of the defining characteristics of BL Lac objects, together with the high polarisation, large amplitude and rapid flux variability. The standard interpretation of these properties, originating from Blandford and Rees back in 1968, is that BL Lacs are radio loud active galactic nuclei (AGN) where the relativistic jet is pointing close to the observer direction, so that the continuum emission is significantly enhanced and the line equivalent width is depressed. BL Lacs therefore offer one of the best opportunities to study relativistic jets, which are manifest from the radio-band to 100 MeV gamma-rays. The atmospheric Cherenkov technique has demonstrated that BL Lacs may emit also in the TeV band. These extremely energetic photons interact with the Extragalactic Background Light (EBL), producing electron/positron pairs. This effect limits the direct detection of such photons to relatively nearby objects ($z < 0.5$).

In the picture of the dominance of relativistic jet emission, though weak, various types of lines are expected: (1) fluorescence emission typical of AGN; (2) stellar absorption of the host galaxy; (3) absorption in the haloes of intervening galaxies. The first two effects may yield directly a redshift z of the object, while the third gives only a lower limit to z.

Because of the difficulty of observing spectral features, alternative procedures for distance estimates have been proposed. One is based on the observed properties of the host galaxy (imaging redshift). This follows from the fact that, at least locally, the host galaxies are all giant ellipticals with a rather narrow distribution in absolute luminosity (Sbarufatti et al. 2005b). Recently the absorption in the TeV band due to EBL has been also used as a redshift probe (Aharonian et al. 2006; Albert et al. 2007).

Because of the imminent launch of the gamma-ray satellites AGILE and GLAST, and of the flourishing of TeV astronomy (HESS, MAGIC, CANGAROO, VERITAS), one expects a substantial increase in the number of BL Lac object candidates. The measurement of their redshift becomes mandatory, since it is not only an important step for the study of the cosmological evolution of the class, but also for tracing the interaction with the host galaxy, and for probing of the EBL.

Motivated by the above considerations we have undertaken a programme of spectroscopic observations of BL Lac objects using the capabilities of the VLT. The main advantage of these observations with respect to previous programmes is the significant improvement in terms of the signal-to-noise (S/N) of the spectra that directly translates into a better capability to detect very weak spectral features, and largely overcomes the results obtained with four-metre-class instruments. This programme makes feasible the redshift detection of faint sources at $z \sim 1$ and beyond, and of relatively nearbyand bright ones, where the beaming effect on the continuum emission is such that spectral lines can be unobservable.

Observations and data analysis

Optical spectra were collected in service mode with FORS1 on the VLT. The observations were obtained in service mode from April 2003 to March 2004 with UT1 and from April to October 2004 with UT2. We used the 300 V + I grism combined with a 2″ slit, yielding a dispersion of 110 Å/mm (corresponding to 2.64 Å/pixel) and a spectral resolution of 15–20 Å covering the 3800–8000 Å interval. The seeing during observations was in the range 0.5–2.5″, with an average of 1″. Detailed information on the observations and the sample objects are given in Sbarufatti et al. (2005a, 2006).

The detection and the measurement of very weak spectral features are difficult to assess because they depend on the choice of the parameters used to define the spectral line and the continuum. In order to apply an objective method for any given spectrum, we evaluate the minimum measurable equivalent width (EW_{min}) defined as twice the rms of the distribution of the EW values measured in 30 Å wide bins from the normalised spectrum (avoiding all strong spectral features).

The procedure for calculating EW_{min} was applied to all featureless or quasi-featureless spectra to find faint spectral lines. All features above the EW_{min} threshold, ranging from 1 Å to 0.1 Å, were considered as line candidates and were carefully visually inspected and measured. Based on the detected lines and the shape of the continuum it is possible to characterise the spectroscopic properties of the objects, confirm or dispute the BL Lac classification and derive new redshifts.

Examples of high S/N spectra of BL Lacs at the VLT

As a direct consequence of the improved signal-to-noise of the optical spectra collected at the VLT, we are able to detect a number of spectral features, either emission from the gas surrounding the nuclear region or absorption lines of the host galaxy. Examples of high S/N VLT spectra are shown in Figures 1 and 2. In the first case (PKS 0808+019) the high S/N spectrum shows clearly two weak emission lines (EW = 3–5 Å) of a moderately high (z = 1.148) redshift object. In the second case (EXO 00556.4-3838) the spectrum allows us to detect the faint absorption features of the host galaxy.

In a third case we show the spectrum of the BL Lac object PG 1553+11. This is a bright (V = 14) object, which, although studied with the most advanced instrumentation, remains line-less (e.g. Falomo and Treves 1990). No signature of its host galaxy is apparent from the high-resolution HST image (Urry et al. 2000 and Scarpa et al. 2000). In this case the spectrum (see Figure 2) obtained with the VLT, in spite of the high (S/N ~ 300), does not allow to detect either faint emission from the nucleus or absorption from the host galaxy.

Analysis of the BL Lac spectra

The observed spectrum of a BL Lac object is given by the contribution of two main components: (1) a non-thermal emission from the nucleus that can be described by a power law; (2) a thermal component due to the host galaxy. In some cases weak emission lines from the nucleus can be also present. Depending on the relative contribution of the two components, the optical spectrum will be dominated by the non-thermal (featureless) emission or by the spectral signature of the host galaxy. In Figure 3 the combination of the two components is compared with the observed spectra for six objects. The host galaxy magnitude deduced from this decomposition is in good agreement with that deduced directly from the image (Sbarufatti et al. 2005b).

Under the assumption that the host galaxy luminosity is confined in a narrow range (e.g. Sbarufatti et al. 2005b) from the EW limits of spectral features, it is possible to constrain the position of the source on the nucleus-to-host flux ratio (ρ) vs redshift plane. This is illustrated in Figure 4. Using this approach it becomes possible therefore to obtain a lower limit to the redshift for objects with featureless spectra (Sbarufatti et al. 2006). For example in the case of PG 1553+11 (Figure 2) the redshift must be $z > 0.1$.

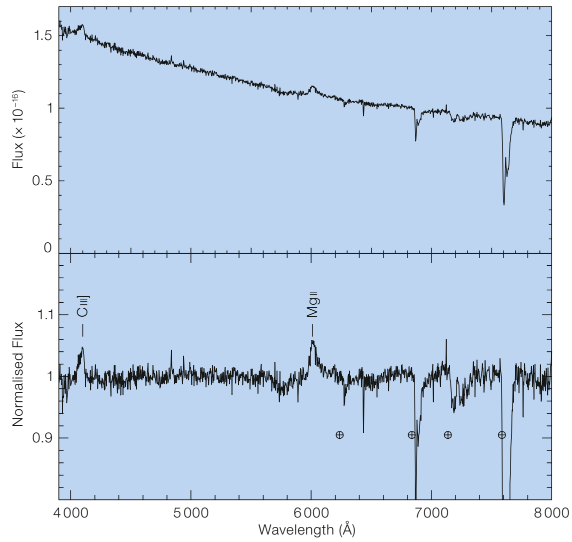

Figure 1a: Optical spectrum of the BL Lac object PKS 0808+019 (z = 1.148). **Top:** Flux-calibrated and dereddened spectra. **Bottom:** Normalised spectrum. Telluric bands are indicated by circled plus signs.

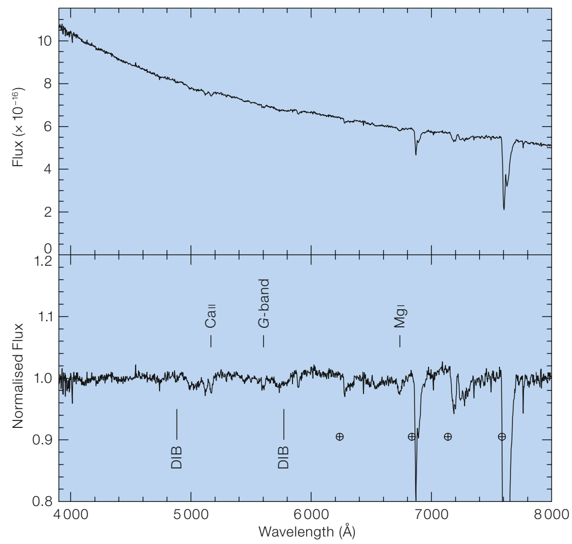

Figure 1b: EXO 00556.4-3838: In this case the spectrum clearly shows the host galaxy spectral features (Ca II 3934, 3968, G-band 4305, and Mg I 5175 Å absorption lines) at z = 0.302. Absorption features in our Galaxy are labelled by DIB (diffuse interstellar band).

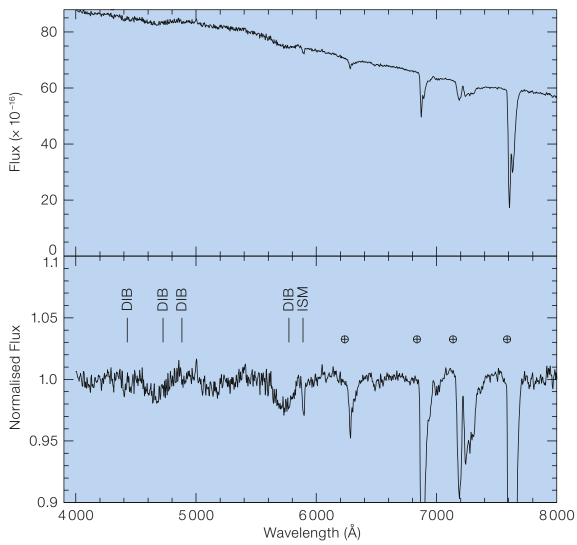

Figure 2: Optical spectrum of the featureless BL Lac object PG 1553+11. **Top:** Flux-calibrated spectra. **Bottom:** Normalised spectra. Telluric bands are indicated by circled plus signs. The other absorption features are identified as interstellar medium (ISM) spectral lines and diffuse interstellar bands (DIB) from gas in our Galaxy.

ZBLLAC – a web page for the spectra of BL Lac objects

The optical spectra of BL Lacs obtained at the VLT have been made available to the astronomical community through a spectroscopic library at the web page: *http://www.oapd.inaf.it/zbllac/index.html*. This includes most of the objects observed at the VLT and others with good quality spectra. For each object in the database we give basic data (coordinates, *V*-band magnitude, the redshift or a lower limit to it), the optical spectrum (in PDF and ASCII table format) and details on the references to the target. In general the best available optical spectrum is linked in the main page of the database, while additional spectra are appended and linked in separate pages. These web pages are also open to external contributions (see *http://www.oapd.inaf.it/zbllac/intro.html* for details).

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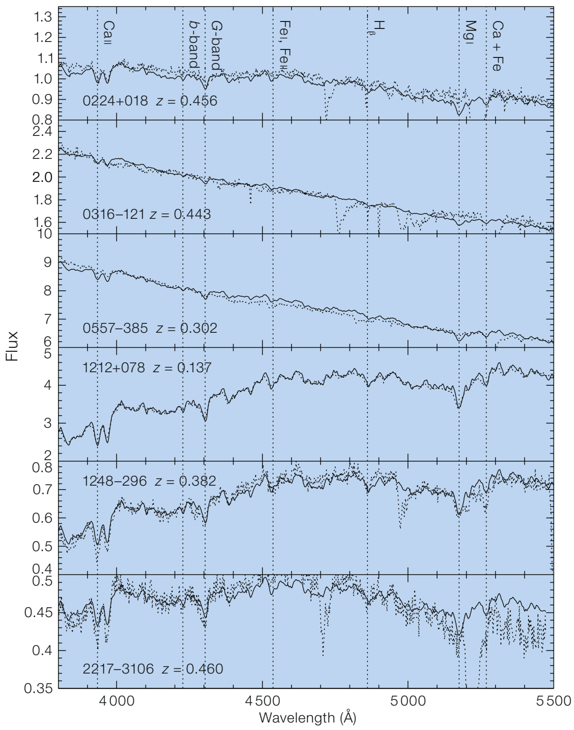

Figure 3: Comparison of the observed optical spectra (dotted line) of BL Lac objects with a best fit model (solid line) composed by a template host galaxy spectrum plus a non-thermal continuum component described by a power law. The figure clearly illustrates the effect on the observed spectrum of the different contributions from the nucleus that occur in 0316–121 and 0557–385.

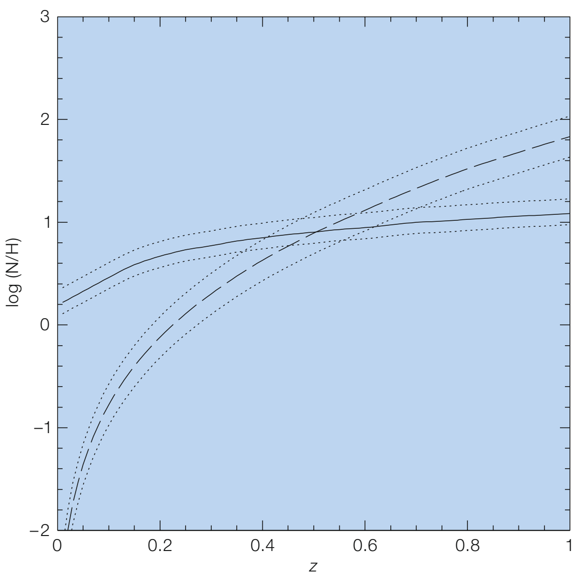

Figure 4: The *R*-band nucleus-to-host ratio (ρ) versus redshift for the BL Lac object 1RXS J150343.0–154107. The solid line represents the limit in this plane obtained from the minimum equivalent width (EW_{min}) that was derived from the VLT spectrum. The bending of this curve at low *z* is due to aperture effects. Dotted curves correspond to a 0.1-Å uncertainty on the EW. The dashed line gives ρ *versus z* for the object with nuclear apparent magnitude R = 17.7 assuming a standard host galaxy ($M_R = -22.9$; Sbarufatti et al. 2005b). Dotted lines encompassing this curve correspond to a variation of 0.5 mag. The intersection of the two solid lines gives the lower limit: $z > 0.5$. Full details on the method are described in Sbarufatti et al. (2006).