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Using Quasars for Cosmology

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Abstract. We briefly review major approaches used to determine fundamental cosmological parameter such as the Hubble constant from quasar observations. We stress how a new understanding of quasar spectral properties may in a not-too-distant future yield estimates of H_0, Ω_M and Ω_Λ.

Key words. quasars: emission lines – galaxies: active – cosmology

1. Introduction

Using quasars to measure cosmological parameters like the Hubble constant H_0, the energy density of matter Ω_M and the one associated to the cosmological constant Λ, Ω_Λ, seems to be an oxymoronic waste of time and effort. First, *quasars are sources with an open-ended luminosity function at low luminosity*: see, e.g., Cheng et al. (1985) for Seyferts and Grazian et al. (2000) for low-z quasars. Second, *quasars are anisotropic sources* in most regions of the electromagnetic spectrum. Two main effects contribute to anisotropy: relativistic beaming in radio-loud sources, and obscuring material co-axial with the accretion disk in both radio-loud and radio-quiet AGN. Beaming and orientation effects are not yet fully understood as far as (a) their influence on optical/UV spectroscopic properties and (b) their occurrence in radio-quiet AGN are concerned (i.e., which radio-quiet AGN are seen pole-on in analogy to radio-loud BL Lacs and OVV quasars?). Third, *spectral parameters of quasars show loose correlations with luminosity.* Basically, the one set of luminosity correlations that survived decades of spectroscopic observations is the so-called *Baldwin effect* [see Sulentic et al. (2000) for a synopsis up to mid-1999, and Dietrich et al. (2002), and Croom et al. (2002) for recent large surveys]. It is a weak anticorrelation between rest-frame equivalent width and continuum luminosity of High Ionization Lines (HILs): CIVλ1549, HeII (λ1640 and λ4686), OVI λ1034. The cosmological expectation of the original, much tighter Baldwin effect correlation did not

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live up to the huge dispersion found in later studies. We can safely conclude that *quasars are the astrophysical opposites of standard candles*!

However, quasars are plentiful: $\sim$13000 are catalogued in the Véron-Cetty & Véron (2001) catalogue 10^{th} edition; data for $\sim$100000 are expected from the Sloan Sky Survey. The exponential growth in number of known quasars between 1970 and 2000 is likely to continue. In the absence of systematic effects, averages can be considered. Quasars are variable and luminous sources, much more luminous than type Ia supernovæ ($M_B \gtrsim$ -30 vs $M_B \approx$ -21.7). Unlike supernovæ, quasars are detected at very high redshift where cosmological effects are most appreciable (as of March 2003: 335 at $z >$ 4, 16 at $z >$5, 4 at z> 6, and growing).

Present (or futuristic) approaches to exploit quasars for cosmology which may be called *time delay methods*, and which include gravitational lenses, accretion disk reverberation, and Broad Line Region reverberation, attempt to utilize the intrinsic variability of individual quasars. After briefly reviewing them, we propose here two methods related to Principal Component Analysis (PCA) that explicitly make use of statistical properties of quasars. The first is based on the so-called "optical plane of the Eigenvector 1 of AGN;" the second can be considered an attempt to strengthen the Baldwin effect by reducing the dependence of CIVλ1549 equivalent width on the Eddington ratio.

2. Time Delay Methods

All time delay methods basically follow a similar procedure: (1) measure an angular separation; (2) measure a linear distance from light travel times (difference); (3) solve for cosmological parameters. An example is the application to gravitationally-lensed images of quasars. Misalignment between lens and quasar yields aymmetrically displaced images. Since quasars are variable light sources, different time delays result for the displaced images. However, differences in time delay are due to both (1) the path-length difference between the quasar and Earth for the light from different images; (2) the Shapiro gravitational time delay for the light rays traveling in slightly different gravitational potentials. The 2^{nd} factor implies model-dependent assumptions. The computed H_0 value is usually below or in agreement with the HST Key project H_0=72±8 Km s^{-1} Mpc^{-1} (Freedman et al. 2001).

A second time-delay method can be based on Broad Line Region reverberation mapping. The basic concept of reverberation mapping is the cross correlation of the continuum and emission line light curves in order to find the temporal shift $\tau_{\rm max}$ that maximizes the correlation (e.g., Peterson 1993). c$\tau_{\rm max}$ provides an emissivity weighted estimate of the BLR linear size. Trouble is that the BLR angular size measurements are prohibitive with present-day technology: for NGC 5548, it is $\tau_{max} \approx$ 21 days; at z =0.017 this means an $d"_{\rm BLR} \approx$ 0.05 marcsecs; even if the BLR linear size increases with luminosity as $\propto L^{0.7}$ (Kaspi et al. 2000), resolution better than 10^{-5} arcsec is still required: 3C273 has $\tau_{\rm max} \approx$ 387 days, at z =0.158 $d"_{\rm BLR} \approx$ 0.01 marcsecs. With the OHANA interferometer expected resolution of 0.2 marcsecs, H_0 can be determined from a couple of nearby Seyfert nuclei (Elvis & Karovska 2002). The method could become fully exploitable if optical/IR interferometers with sufficient angular resolution come into service in the future.

A similar approach has been based on the wavelength-dependent time delays between continuum flux variations (Collier et al. 1999). Basically the observed delay $\tau(\lambda)$ wavelength-dependence allows to determine the disk radial temperature T(r); the observed specific flux is then $f_\nu \propto \tau^2 D^{-2} \lambda^{-3}$. This relationship can give an H_0-independent distance. The method yields $H_0 \approx$ 42±9 km s^{-1} Mpc^{-1} from NGC 7469 data. No angular size measurement is required at the expense of a major assumption: the existence of a geometrically thin, optically thick Shakura-Sunyaev disk.

3. Methods Related to Multivariate Analysis of Quasars Spectral Properties

Two main (sets of) correlations systematize the spread of observed properties among AGN (Sulentic et al. 2000): the so-called "Eigenvector 1" (E1) correlations originally identified by Boroson & Green (1992) through a PCA of several optical spectral properties of ≈80 Palomar-Green quasars. PCA yields a set of m (≤n) orthogonal vectors which are: (1) linear combinations of the original n variables and (2) the eigenvectors of the covariance matrix. The eigenvalues yield the variance associated to each eigenvector. At the very least PCA identifies the "dimensionality of the problem." For AGN, the minimum dimension of the parameter space based on the eigenvectors is 2; however, a 3D parameter space accounts better for the AGN phenomenology (see below).

The first eigenvector is related to an anticorrelation between the strength of FeII and [OIII]$\lambda\lambda$4959,5007 and the width of Hβ and of other Low Ionization Lines (LILs): HI Balmer lines, MgIIλ2800, FeII multiplets. It is *very robust*: it keeps coming out in large and small samples alike (see, e.g., Shang et al. 2003). The second eigenvector is associated to the luminosity dependence of HILs equivalent width i.e., to the Baldwin effect.

3.1. Interpretation of the Eigenvector 1

The "optical plane" H$\beta_{\rm BC}$ FWHM and $\rm R_{FeII}$ = W(FeIIλ4570)/W($H\beta_{\rm BC}$) provides a very good representation of E1 (Sulentic et al. 2000). The main physical parameters influencing the location of points in this plane are the Eddington ratio $\rm L/L_{Edd}$ ($\propto$ L/M) and the black hole mass M, if we consider a large M range (3-4 orders of magnitude, Zamanov & Marziani 2002). If LILs (H$\beta_{\rm BC}$ and FeII) are emitted in a flattened system, the effect of orientation can be quite dramatic as shown by Fig. 4 of Marziani et al. (2001): even with a fixed mass, it is possible to explain the plane occupation of a PG-dominated sample. However, L/M accounts for the AGN sequence in the plane. Black hole mass and orientation act as source of scatter.

3.2. Making the Most of the Eigenvector 1 Optical Plane for Cosmology

Supernova Cosmology Project results supporting $\Lambda \neq 0$ are still highly uncertain. The expected effect is just a few tens of magnitude at $z \approx 0.6$, and goes down to 0 at $z \approx 1.5$. A robust verification of a cosmological model with $\Omega_{\rm M} \approx 0.28$ and $\Omega_\Lambda \approx 0.72$ would require accurate measurements for sources in the range $0.6 \lesssim z \lesssim 3$, as it can be seen from the Hubble diagram with type Ia supernovæ (Riess et al. 2001).

Instruments like VLT/ISAAC make possible observations of intermediate redshift quasars ($1 \lesssim z \lesssim 2.2$) with S/N and resolution sufficient to apply the same data analysis procedure used for optical spectra (e.g., Sulentic et al. 2003, in preparation), which can in turn be applied to $z \lesssim 1$. E1 parameters can be easily measured with comparable accuracy, and an "optical" E1 diagram with an intermediate$-z$ quasar extension can be easily drawn. In principle, since the major effects are due to L/M and M, from the location in the E1 plane, a redshift independent estimate of L can be obtained from the location of the quasar in the optical E1 plane alone. In practice, however, two major pieces of information are needed. First, the relationship between L/M and M and $\rm R_{FeII}$ and FWHM(H$\beta_{\rm BC}$) should be calibrated from SED observations and virial mass determinations for low-z objects rather than exclusively from a theoretical model. The second requirement is that orientation needs to be estimated on an object-by-object basis, and a correction applied.

The previous discussion refers us to a reliable orientation indicator. This could be provided by shift (with respect to the quasar rest frame) and other parameters of the CIVλ1549 line. In several sources with FWHM(H$\beta_{\rm BC}$)$\lesssim$4000 km s^{-1} (including Narrow Line Seyfert 1 nuclei) CIVλ1549 shows a blueshifted profile that is disjoint from the unshifted, Lorentzian profile of H$\beta_{\rm BC}$. The easiest interpretation is that while LILs are emitted in a flattened configuration, HILs are emitted by outflowing gas, possibly associated with a disk-wind. In the case of a radiation pressure driven wind, the shift and profile shape should be sensitive to both L/M and i. Therefore, CIVλ1549 measurements may provide an independent estimate of orientation, and hence a 3D observational parameter space to map into a 3D physical space (i, L/M, M) that will ultimately yield the luminosity.

3.3. *The Baldwin Effect in an Ideal Universe*

The utility of the CIVλ1549 line goes beyond an estimate of the orientation angle. A PCA which includes CIV would make the most of the Baldwin Effect (Shang et al. 2003, Bachev, Marziani, Sulentic, et al. 2003, in preparation). There is a strong dependence on Eddington ratio of the equivalent width of CIVλ1549 at low z (and luminosity): W(CIVλ1549) is minimum for Narrow Line Seyfert 1 galaxies ($\sim$20–30Å) which are believed to be the highest Eddington ratio sources in the local Universe, and is similar to the rest frame value of high-z quasars). Using an extended spectral parameter collection including UV and optical emission lines it may be possible to obtain a "principal component" that minimizes dependence of W(CIV) on L/M and produces a "Baldwin effect" with a much lower scatter.

4. Conclusions

High S/N mid-IR observations covering Hβ have a tremendous potential for constraining the main cosmological parameters, provided that: (a) a reliable orientation indicator is obtained for each quasar; (b) a collection of UV/optical rest frame quasar parameters for a wide range of z is obtained for optical/UV PCA. Of course, BLR reverberation will do the job at best in a hopefully not-too-far future, but PCA methods are likely to be feasible with present-day observational capabilities.

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