New Astronomy 16 (2011) 122–127

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Unusual double-peaked emission in the SDSS quasar J093201.60 + 031858.7

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ARTICLE INFO

Article history:
Received 28 September 2009
Received in revised form 12 July 2010
Accepted 11 August 2010
Available online 15 August 2010
Communicated by G. Brunetti

Keywords:
Accretion disks
Galaxies: active
Quasars: emission lines
Black holes

ABSTRACT

We examine spectral properties of the SDSS quasar J093201.60 + 031858.7, in particular the presence of strong blue peaks in the Balmer emission lines offset from the narrow lines by approximately 4200 km s^{-1}. Asymmetry in the broad central component of the Hβ line indicates the presence of a double-peaked emitter. However, the strength and sharpness of the blue Hβ and blue Hγ peaks make this quasar spectrum unique among double-peaked emitters identified from SDSS spectra. We fit a disk model to the Hβ line and compare this object with other unusual double-peaked quasar spectra, particularly candidate binary supermassive black holes (SMBHs). Under the binary SMBH scenario, we test the applicability of a model in which a second SMBH may produce the strong blue peak in the Balmer lines of a double-peaked emitter. If there were only one SMBH, a circular, Keplerian disk model fit would be insufficient, indicating some sort of asymmetry is required to produce the strength of the blue peak. In either case, understanding the nature of the complex line emission in this object will aid in further discrimination between a single SMBH with a complex accretion disk and the actual case of a binary SMBH.
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1. Introduction

Quasars and active galactic nuclei (AGN) with spectra showing double-peaked emission lines are an interesting class of objects, though in many cases the origin of the double-peaks is not fully understood. Some of these spectral features have been examined in the context of emission from an accretion disk. These objects are commonly known as double-peaked emitters (or disk emitters) and have been the subjects of a number of studies (Eracleous and Halpern, 1994, 2003; Strateva et al., 2003). Double-peaked emitters are important objects to study because the double-peaked profiles provide information about the structure of the accretion disk around supermassive black holes (SMBHs). The disk profiles are typically centered around Balmer emission line positions presumably because of photoionization and electron scattering in a geometrically thin disk (Chen and Halpern, 1989). In the disk profiles, there is typically a peak on the red side and a peak on the blue side of the central emission line, though in some cases the peaks are very broad and shallow. Furthermore, the blue peaks are typically stronger than the red peaks because of relativistic beaming.

For many double-peaked emitters, a simple (circular, Keplerian) disk model provides a satisfactory model. However, this sub-class of AGN contains a range of Balmer emission line profiles, and in some cases the fits require additional complexities (i.e. asymmetries) such as eccentricity in the disk or a hot spot on the disk surface. In a few cases, only one peak appears to be offset from the narrow lines, and such objects have been interpreted as candidate binary or recoiling SMBHs because the spectra resemble multiple emission line regions. These interpretations are important to consider because binary and/or recoiling SMBHs are expected to result from galaxy mergers (Merritt et al., 2004; Komossa, 2006) and therefore many such cases should exist. Additionally, they are believed to play a role in the evolution of the SMBH population (Hopkins et al., 2005). Therefore, there has been much interest in the possibility of identifying close binary SMBHs by locating double-peaked emission lines in the spectra of AGN and quasars (Gaskell, 1996; Zhou et al., 2004). In these cases, determining the true physical origin of the double-peaks is difficult since they may be partly or entirely due to complex disk emission instead. Interestingly, a few candidate binaries have been identified. For example, the object SDSS J153636.22 + 044127.0 (from here on SDSSJ1536 + 0441) has been interpreted as a binary SMBH (Boroson and Lauer, 2009), a disk emitter (Chornock et al., 2010), and as both (Tang and Grindlay, 2009). Another candidate, SDSS J105041.35 + 345631.3 (from here on SDSSJ1050 + 3456) shows similar features and was first identified by Shields et al. (2009) as a possible recoiling or binary SMBH. A third candidate, SDSS J092712.65 + 294344.0 (from here

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doi:10.1016/j.newast.2010.08.004

on SDSSJ0927 + 2943), was first identified and interpreted as a recoiling SMBH (Komossa et al., 2008), and more recently also as a binary SMBH (Bogdanović et al., 2009b; Dotti et al., 2009). The diversity of these interpretations indicates that accretion processes around a singe SMBH or in a binary SMBH are expected to produce a range of complex spectral signatures. Results from simulations indicate that profiles of close binaries strongly resemble those of double-peaked emitters (Bogdanović et al., 2008, 2009a); therefore, it is important to examine double-peaked profiles, particularly those with strong and distinct multiple peaks, as evidence for complex accretion processes that may be the result of a binary SMBH.

Inspired by the above mentioned previous searches and their results, we performed a similar search through the Sloan Digital Sky Survey (SDSS) archives to identify spectra with double-peaked emission lines at $z < 0.89$; this redshift limit was chosen so that all spectra would include the Hβ line. All matches were individually inspected. In this paper, we describe the spectrum of a quasar, SDSS J093201.60 + 031,858 (from here on SDSSJ0932 + 0318), that has a blue set of Balmer emission lines offset from the narrow lines by approximately 4200 km s^{-1}. While the Hβ line has a broad, red peak that is indicative of a double-peaked emitter, it has unusually strong blue Hβ and Hγ peaks that are unusual among SDSS identified double-peaked emitters. We examine similarities and differences between the features of SDSSJ0932 + 0318 and those of other unusual double-peaked emitters, particularly candidate binary SMBHs, to help determine the physical nature of the line emission. Throughout the paper we adopt the cosmological parameters $H_o = 71$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$ and $\Omega_{vac} = 0.73$.

2. Spectral analysis

2.1. The continuum

The quasar spectrum we discuss was drawn from the fourth edition of the SDSS quasar catalogue (Schneider et al., 2007). It has SDSS point source magnitudes of $u = 18.731$, $g = 18.460$, $r = 18.386$, $i = 18.271$ and $z = 17.945$. Using the suggested conversion from Jester et al. (2005), $B = g - 0.17(u - g) + 0.11$, yields $B = 18.39$, which is also corrected for a Galactic color excess of $E(B - V) = 0.053$, taken from the NASA Extragalactic database following the model of Schlegel et al. (1998). Converting to a bolometric luminosity (Marconi et al., 2004) and correcting for a stellar contribution of 33% (the mean value from Eracleous and Halpern (2003)) yields $L_{BOL} = 4.25 \times 10^{45}$ erg s^{-1}. The spectrum was corrected for Galactic extinction using the IRAF task 'dereden.' Since disk emission is evident in the spectrum (Fig. 1), the line of sight to the central SMBH is probably not significantly obscured so we did not correct for internal extinction. The continuum slope was modeled as a power law ($f_\lambda = \lambda^{-\alpha}$), and the best fit continuum slope has an index of $\alpha = 2.05$.

2.2. The disk profile

The Hα line has been redshifted almost entirely out of the spectrum, therefore we primarily focus on the Hβ/[OIII] complex. To fit the asymmetric line profile and to test the applicability of the disk emitter scenario, we fit a disk profile to this region. The disk model was centered at the redshift of the [OIII]5007 line based on the assumption that it represents the redshift of the central SMBH (discussed in Section 3.2). The disk model we used was adopted from Chen and Halpern (1989) and assumes a circular, Keplerian disk. The assumption of circular shape is used since an accretion disk, in the absence of external influences, should be circularized due to the energy loss within the disk. In the model, which has been

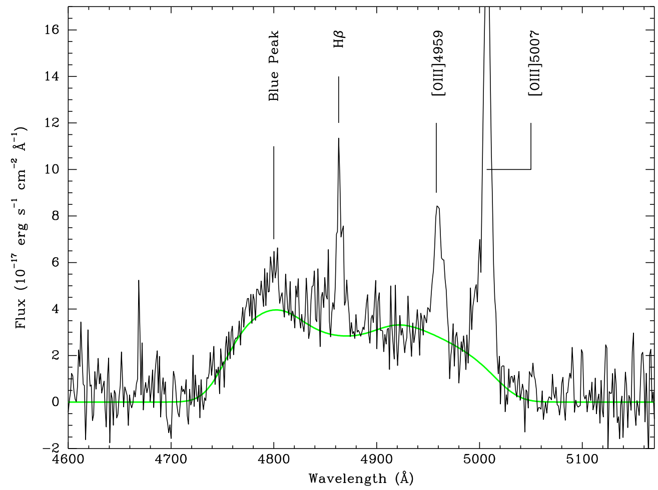

Fig. 1. Hβ/[OIII] complex at the rest wavelength with the disk profile overlaid. The central wavelength of the disk model is set to the position of the narrow Hβ line. The parameters of the fit are as follows: $q = 3$, $\sigma = 1000$ km s^{-1}, $i = 30°$, $\xi_1 = 225r_g$ and $\xi_2 = 2700r_g$. Notice the strong blue peak that is not adequately fit by the circular, Keplerian disk model.

widely used to model double-peaked profiles, the parameters are as follows: the local broadening of the line (σ), the inclination of the disk (i), the inner and outer radii of the disk (ξ_1 and ξ_2) in gravitational units (r_g), and emissivity as a function of radius on the disk ($\epsilon = \xi^{-q}$) where q is a dimensionless power law index. In previous uses of this model, the power law index q is usually constrained near 3. Therefore, we have set $q = 3$ to minimize the number of free parameters. The local broadening tends to range from $\sigma \approx 500$ to 2000 km s^{-1}, and we used a value of 1000 km s^{-1} which is within that range and typical of disk model fits in the literature. The inclination, inner radius and outer radius are therefore the three parameters that we adjusted to find the best fit, and each best fit was obtained by eye with the restriction that the fit be bounded by the observed emission line as was done in Chen and Halpern (1989). We fixed the inclination at three values, 15°, 30°, and 45°, and varied the inner and outer radii to obtain the best fit for each inclination. For 15°, the best fit produces a sharp red peak that does not match the broad, shallow red peak that is observed. In contrast, for 45°, the best fit does not produce the extended red wing that is blended with the [OIII] emission lines. We adopted an inclination of $i = 30°$ and inner and outer radii of $\xi_1 = 225r_g$ and $\xi_2 = 2700r_g$, respectively, for which the broad and shallow red peak is best fit (Fig. 1). This is important since, after subtraction of the disk and subsequent fitting of the emission lines (Section 2.3), the [OIII]5007/[OIII]4959 ratio is ~3, in agreement with atomic theory. The correct position of the blue peak is also produced when these parameters are used. However, in none of the fits does the symmetric disk profile account for all of the flux in the blue peak which is unusually strong for a double-peaked emitter. A similar fit was performed on the Hγ region. Though the Hγ emission is weaker and a fit is more difficult, it is clear that a symmetric disk profile is not sufficient there for the same reason that the blue Hβ peak is not well modeled.

2.3. Emission lines

After subtraction of the disk profile, Gaussian profiles were fit to the broad and narrow central components of the Hβ/[OIII] and Hγ regions using the IRAF task 'fitprofs.' In the Hβ/[OIII] region all parameters of the fit (peak position, peak flux and FWHM) are left as free parameters, but the peak position and FWHM in the Hγ re-

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