Mem. S.A.It. Vol. 84, 719

Memorie della

High redshift blazars

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Abstract. Blazars are sources whose jet is pointing at us. Since their jets are relativistic, the flux is greatly amplified in the direction of motion, making blazars the most powerful persistent objects in the Universe. This is true at all frequencies, but especially where their spectrum peaks. Although the spectrum of moderate powerful sources peaks in the ~GeV range, extremely powerful sources at high redshifts peak in the ~MeV band. This implies that the hard X–ray band is the optimal one to find powerful blazars beyond a redshift of ~4. First indications strongly suggest that powerful high–z blazars harbor the most massive and active early black holes, exceeding a billion solar masses. Since for each detected blazars there must exist hundreds of similar, but misaligned, sources, the search for high–z blazars is becoming competitive with the search of early massive black holes using radio–quiet quasars. Finding how the two populations of black holes (one in jetted sources, the other in radio–quiet objects) evolve in redshift will shed light on the growth of the most massive black holes and possibly on the feedback between the central engine and the rest of the host galaxy.

Key words. galaxies: active — quasars: general — quasars: individual: B2 1023+25 — X-rays: general.

1. Introduction

Blazars are Active Galactic Nuclei (AGN) with powerful relativistic jets pointing close to our line of sight. How close? A convenient definition is to require that the viewing angle $\theta_v < 1/\Gamma$, where Γ is the bulk Lorentz factor of the emitting plasma in the jet. With this definition for each detected blazar other $2\Gamma^2 = 200(\Gamma/10)^2$ misaligned sources sharing the same intrinsic properties, but appearing dramatically different, must exist. The enhancement due to relativistic beaming makes blazars visible even at high redshifts, and this makes them extraordinary probes to explore the far Universe. Since radio–quiet quasars are ~10 times more numerous than radio–loud quasars, and $\sim 10^3$ times more numerous than blazars the detection of high–z blazars implies the existence of a much larger population of similar sources. In particular, if the black hole mass of a blazar at $z = 5$ is larger than a billion solar masses, there must exist hundreds of equally heavy black holes among the misaligned sources. This motivates our search for high–z blazars, since it is competitive with the analogous search of heavy black holes in high–z radio–quiet quasars.

There are hints that radio–loud sources are associated to larger black hole masses (e.g. Laor 2000; Chiaberge & Marconi 2011, but see

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Woo & Urry 2002) and to very massive elliptical hosts (with the possible exception of radio loud Narrow Line Seyfert 1 galaxies, see Foschini et al. 2011). This makes us wonder if this is true also at large redshifts (i.e. $z > 3-4$). Is the presence of a relativistic jet associated to a black hole of a larger size even when the first supermassive black holes were formed?

2. The SED of powerful high–z blazars

Fig. 1 shows the SED of PKS 0227–369 (z = 2.115), a typical powerful and γ–ray bright blazar. Detected by the *Fermi* satellite, its apparent γ–ray luminosity exceeds 10^{48} erg s^{-1}. The γ–ray component dominates over the synchrotron luminosity by almost two orders of magnitude. Therefore the magnetic field in the emitting region cannot be too large, and this is the reason why the jet cannot be magnetically dominated at the jet scales where most of the luminosity is produced (e.g. Celotti & Ghisellini 2008). The peak of the synchrotron emission lies in the mm range, and the steep synchrotron spectrum beyond the peak lets the accretion disk flux to dominate the optical–UV spectrum. Applying a simple Shakura & Sunyaev (1973) disk emission model we can fit the contribution of the disk to the SED, and find the black hole mass M and the disk luminosity L_d. In addition, we can estimate L_d using the broad emission lines (these powerful blazars are all Flat Spectrum Radio Quasars, with strong broad optical emission lines), especially when the optical continuum is contaminated by some non–thermal synchrotron flux. Details of the method can be found in Calderone et al. (2013).

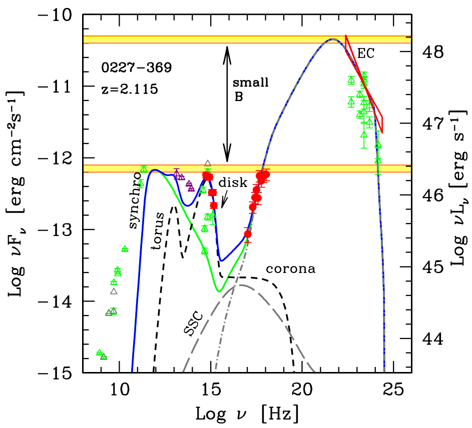

Fig. 1. The SED of PKS 0227–369, a γ–ray bright blazar at z = 2.115, detected by the *Fermi* satellite. Data (references in Ghisellini et al. 2009) have been updated with the *WISE* far IR fluxes. Solid (red) circles are simultaneous *Swift*/UVOT and XRT data, empty triangles are archival data. The solid blue line is the result of applying a one–zone leptonic model (Ghisellini & Tavecchio 2009): the different components are labelled. The large Compton to synchrotron ratio (see the horizontal bars), that is common in these powerful sources, set limits on the strength of the magnetic field. The accretion disk emission is well visible.

2.1. Hard X–rays are better than γ–rays

Fig. 2 shows the SED of two powerful blazars, at different redshifts: MG3 215155+2217 (z=3.668) is a strong hard X-ray source, detected by the BAT instrument [15–150 keV] onboard the *Swift* satellite, but not by *Fermi*. On the contrary PKS 0347–221 is a very powerful *Fermi* source, but weaker in the X–ray band, and not detected by BAT. This is due to the different location of the high energy peak, which falls at lower frequencies in MG3 215155+2217, the more powerful source. This in agreement with the *phenomenological blazar sequence* (Fossati et al. 1998). Furthermore, for increasing redshift, the K–correction favors the detection of the hard X–ray flux and works against the detection of the steep γ–ray component.

For these two reasons the best way of finding high–z blazars is through observations in the hard X–ray band, close to where the high energy component peaks in very powerful sources. It is not by chance that BAT detects blazars at a larger redshift than *Fermi*/LAT (see Ajello et al. 2009; 2012). Therefore the best way to find high redshift blazars would be a survey in the hard X–rays (above 10 keV), as was envisaged by the *EXIST* mission (Grindlay et al. 2010; see also Ghisellini et al. 2010a for the number of detectable high–z blazars). In the absence of a hard X–ray survey, we must

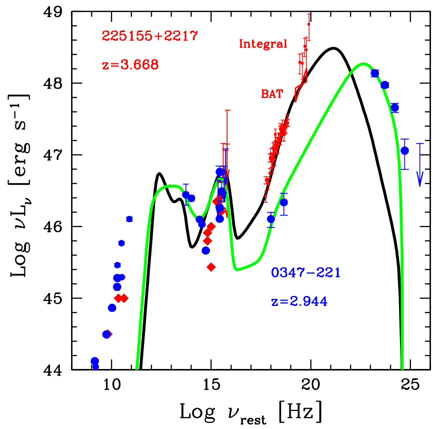

Fig. 2. The SED of PKS 0347–211 (filled blue circles) compared to MG3 225155+2217 (red diamonds; Ghisellini et al. 2009), to show that the most powerful blazars at high redshifts are relatively weaker γ–ray and stronger hard X–ray sources. This is due to the shift to smaller frequencies of the emission peaks (according to the so called *blazar sequence,* Fossati et al. 1998). To this intrinsic effect we must add the impact of the K–correction, that favors the hard X–ray band of sources at a larger redshift.

find good blazar *candidates* on the basis of observations coming from the radio and optical (giving us the radio–loudness and the redshift) and from the X–rays (flux and slope). Then we should confirm the blazar nature through dedicated observations in the hard X–ray band.

Why is it so crucial to observe at high X–ray energies? Because at these frequencies we are close to the emission peak of the jet emission: a large hard X–ray to optical ratio indicates a highly beamed source. The same indication comes from the radio–loudness, if the optical is dominated by the unbeamed accretion disk flux, and the radio by the beamed jet (in principle, at 1.4 GHz there might be some contribution from the unbeamed radio–lobe, even if it is unlikely for high–z sources). The added value of the X–ray data (and their crucial role in classifying the source as a blazar) comes because in blazars the main radiation process at these frequencies is inverse Compton scattering by relativistic electrons in the jet on the seed photons produced in the broad line region (BLR) and, possibly on, the IR photons from the dusty torus (this process is called *External* Compton, or EC for short). In the comoving frame, the seed photons are highly anisotropic, making the scattered flux anisotropic even in the comoving frame (Dermer 1995). In the observer frame, this translates in a beaming pattern different than that of the synchrotron flux (more enhanced in the forward direction and more depressed at large angles). Therefore, for decreasing viewing angles, the X–ray (EC) flux increases more than the radio (synchrotron) flux. Furthermore, the [0.3–10 keV] X–ray EC spectrum is predicted to be very hard, even harder than $\alpha_X \sim 0.5$, where α_X is defined through $F(\nu) \propto \nu^{-\alpha_X}$.

3. Chasing high redshift blazars

The record holder of the largest redshift for blazars is Q0906+6930, with $z = 5.47$ (Romani et al. 2004). There is a possible association of this object with an EGRET source (but the γ–ray detection is only at the $\sim 3\sigma$ significance level), while *Fermi*/LAT did not detect it (yet). Romani (2006) estimated a virial black hole mass $M \sim 2 \times 10^9 M_\odot$.

The discovery of this blazar came serendipitously, not through the study of a well defined sample, in terms of flux limit and covered sky area. Since the comoving volume between $z = 5$ and $z = 6$ is 380 Gpc^3, its existence implies the existence of more than $450(\Gamma/15)^2/380 \sim 1$ Gpc^{-3} black holes with mass $M > 10^9 M_\odot$ in this redshift bin (see Fig. 16 in Ghisellini et al. 2010a). This is not much smaller than the number density of radio–quiet quasars of optical luminosity larger than 10^{47} erg s^{-1} (Hopkins et al. 2007), that must host a black hole heavier than a billion solar masses not to become super–Eddington (see Volonteri et al. 2011 for a discussion about the radio–loud fraction at these redshifts and the problem of the paucity of radio–loud sources in the SDSS+FIRST survey).

Ajello et al. (2009) studied the blazars detected by the *Swift*/BAT instrument, restricting the energy range to [15–55 keV] to have a cleaner signal. They also derived the luminosity function of these hard X–ray blazars, and noted that the number density of the most powerful objects [above $\log(L_X/\mathrm{erg\,s^{-1}}) = 47.2$] has a well pronounced peak around $z \sim 4$. We (Ghisellini et al. 2010a) have modeled these powerful objects and found that all have a black hole with $M > 10^9 M_\odot$, accreting on average at the ~10% Eddington rate. The relatively large $L_\mathrm{d}/L_\mathrm{Edd}$ ratio tells us that we are observing the end of the formation process of a heavy black hole.

We then started another approach to find high–z blazar candidates in a systematic way. We selected all SDSS quasars (Shen et al. 2011) that are also detected by the FIRST survey (at 1.4 GHz) with a flux limit around 1 mJy) above $z = 4$. To select sources with a small viewing angle, we also required the radio–loudness R to be larger than 100 [$R \equiv F(5\,\mathrm{GHz})/F(2500\text{Å})$]. We find 31 objects, including 3 objects at $z > 5$. Of these 31 sources, 19 were observable from La Silla (Chile) with the GROND instrument (Greiner et al. 2008), which observes simultaneously in 3 IR and 4 optical filters. Together with the far IR data from *WISE*, we obtain a very good coverage of the IR–optical spectrum, where is expected the peak of the accretion disk component (at these redshifts). The results of this study are in preparation (Sbarrato et al. 2013), but during this work we realized that the most distant source of the sample (at $z \simeq 5.3$) was also the best candidate to be a blazar with a large black hole mass. This source is described below.

3.1. The second most distant blazar

Sbarrato et al. (2012) realized that B2 1023+25 (at $z = 5.3$) was a very good blazar candidate, on the basis of its very large radio–loudness ($R \sim 5,000$) and radio flux (261 and 106 mJy at 1.4 and 8.4 GHz, respectively). Fig. 3 shows the IR–optical SED: thanks to the photometric *WISE* and GROND observations and partially the SDSS spectrum [absorbed blueward of Lyα ($\log\nu \sim 15.4$)], we could determine, in a reliable way, the black hole mass: $M \sim 3\times10^9 M_\odot$, with an uncertainty of less than a factor 2. We also found that the disk luminosity is ~1/4 Eddington.

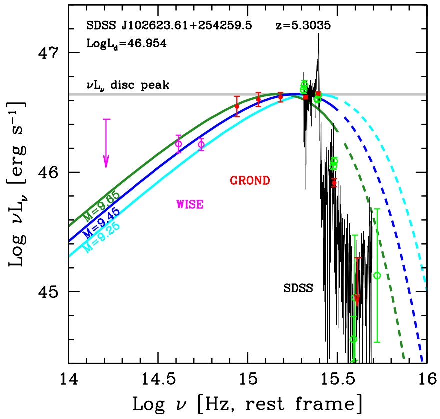

Fig. 3. The IR to optical SED of B2 1023+25. Data are from *WISE* (far–IR) GROND (IR–optical) and SDSS (optical, absorbed blueward of the the Lyα line. Archival data are shown as empty circles. We show three Shakura & Sunyaev disk spectra, with the same L_d but slightly different masses (whose logarithmic value is labelled), to appreciate the uncertainties related to the mass estimate. From Sbarrato et al. (2012).

Then we requested a ToO observation from the *Swift* team, in order to confirm our hypothesis. The total exposure of the *Swift*/XRT instrument [0.3–10 keV] was ~10 ks and resulted in 26 counts. Despite the small number of detected photons, the X–ray flux and slope was found to be entirely consistent with the blazar hypothesis. Fig. 4 shows the entire SED of the source, and compares it with the SED of Q0906+6930. The two SEDs are almost identical. The X–ray flux is strong and hard: even in the relatively soft *Swift*/XRT band the X–ray flux exceeds the accretion disk flux. The same figure shows the limiting (differential) flux of *NuStar* for an exposure of 1 Ms. It is clear that both B2 1023+25 and Q0906+6930 can be detected by *NuStar* up to 80 keV with a very short exposure. If the flux keeps to be hard up to a few tens of keV, this would be the final proof of the blazar nature of both objects.

This is important, since if these two sources are blazars (namely, if their $\theta_\mathrm{v} < 1/\Gamma$), we can estimate how many similar but misaligned sources there are in this redshift bin.

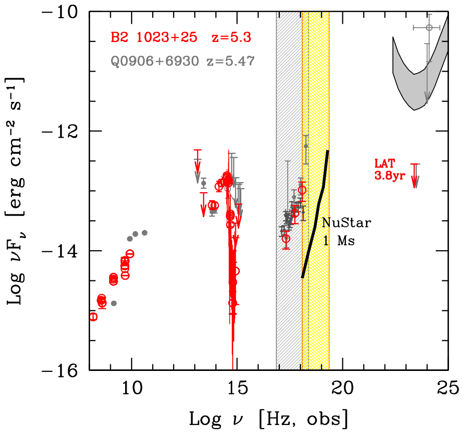

Fig. 4. The entire SED of B2 1023+25 (larger empty circles) compared to the SED of Q0906+6930 (smaller grey filled circles). Note that they are almost identical, apart from the EGRET (uncertain) detection. Note also the upper limit given by *Fermi*/LAT. We show the limiting flux of *NuStar* for 1 Ms exposure time. Both sources could be detected by *NuStar* in $\sim 10^4$ s. From Sbarrato et al. (2012).

Assuming that B2 1023+25 is indeed viewed at $\theta_{\rm v} < 1/\Gamma \sim 3.8°(15/\Gamma)$, then there must be other $\sim 450(\Gamma/15)^2$ sources with a black hole mass similar to B2 1023+25, with similar redshift, and in the portion of the sky covered by the SDSS+FIRST survey. The latter covers 8,770 square degrees. Therefore, in the redshift bin $5 < z < 6$, the existence of B2 1023+25 implies the existence of other $450(\Gamma/15)^2(40,0000/8,770) \sim 2,000$ jetted sources in the whole sky and in the same redshift bin, all having a black hole mass $M > 10^9 M_\odot$. Dividing by the comoving volume (i.e. 380 Gpc^3) we derive a density $\phi(M > 10^9 M_\odot)$=5.4 Gpc^{-3} in the $5 < z < 6$ redshift bin. Note that this is a lower limit, since other high redshift blazars could exist, but not yet identified as such (the existence of Q0906+6930 does not change this estimate, since it is one of the blazars expected in the portion of the sky not covered by the SDSS+FIRST survey).

4. Early supermassive black holes

At a redshift $z = 5.3$, the age of the Universe is 1 billion years. This is a strict upper limit for the time needed to build up a black hole of mass equal to $3 \times 10^9 M_\odot$. If the black hole accretes at the rate $\dot{M}$, and produces a luminosity $L_{\rm d} = \eta \dot{M} c^2$, the time needed to double the black hole mass is the Salpeter time $t_{\rm S}$:

$$t_{\rm S} = \frac{\eta \sigma_{\rm T} c}{4\pi G m_{\rm p}} \frac{L_{\rm Edd}}{L_{\rm d}} \sim 45\, \eta_{-1} \frac{L_{\rm Edd}}{L_{\rm d}} \ {\rm Myr} \qquad (1)$$

where $\eta = 10^{-1}\eta_{-1}$. Assuming a black hole seed of mass M_0, and that the accretion process occurs always with the same efficiency η, the time Δt needed to build up the final mass M is

$$\Delta t = t_{\rm S} \ln\left(\frac{M}{M_0}\right) \qquad (2)$$

If accretion occurs at the Eddington rate all the time, with $\eta = 10^{-1}$, the time needed to reach $3 \times 10^9 M_\odot$ is 0.77 or 0.46 Gyr for a seed mass of 100 or 10^5 solar masses, respectively. If we find a similar black hole mass at $z = 7$, when the Universe was 0.75 Gyr old, then we can exclude that the black hole seed had the mass of typical PopIII star remnant black holes, or else that the accretion was always near or sub–Eddington, or that the efficiency was as large as 10%.

Indeed, Mortlock et al. (2011) found a radio–quiet quasar, ULAS J1120+0641, at z = 7.085 hosting a black hole with a mass $M \sim 2 \times 10^9 M_\odot$. This was estimated through the virial method (i.e. FWHM of the MgII broad line and the optical continuum luminosity). If true, this high value for the black hole mass is difficult to reconcile with the simple scenario of black hole growth through accretion at the Eddington rate and with $\eta \sim$0.1.

5. Conclusions

The rationale for using blazars as probes of the far Universe is based on the fact that they are very powerful, and can be detected at very large redshifts. While in the optical they are identical to radio–quiet quasars, their X–ray emission stands out, especially at large energies (tens of keV), since their X–ray spectrum is hard. Therefore hard X–ray surveys would be the best way to find them out. In these objects we can observe at the same time the non–thermal jet emission and the accretion disk component, left "naked" (i.e. not covered) by the synchrotron flux that peaks in the mm band and has a steep spectrum after the peak.

Besides their cosmological use, in these sources we can directly study how the power of the jet is associated to the accretion rate. A strong correlation is present (Ghisellini et al. 2010b; Sbarrato et al. 2012), with the jet power that is often larger than the disk luminosity. The finding that jetted AGNs reside on average host black holes of larger mass than radio–quiet ones is intriguing, albeit controversial, and we hope to investigate this very issue at redshifts larger than 4. To this aim, while awaiting for hard X–ray mission capable of performing surveys deeper than BAT or INTEGRAL, we must rely on large radio and optical surveys (i.e. SDSS+FIRST) and be able to select the best high–z blazar candidates, to be confirmed by dedicated X–ray observations, preferentially in the hard band, above 10 keV.

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