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Blazars

Up to the seventeenth century, the unaided eye was the only receiver that humanity could use to observe the Universe. Evolution was able to adapt this "instrument" to be sensitive to the light of the star we happen to be orbiting, the Sun. The invention of the telescope amplified the sensitivity of the eye and its angular resolution, letting humanity discover, less than a century ago, that other galaxies exist, far beyond the Milky way, and that these galaxies are moving apart: the Universe expands. However, all we could discover using the eye and its extension, the optical telescope, regarded a tiny, very tiny, part of the entire electromagnetic spectrum. As soon as technology enabled us to open new windows, we discovered other phenomena, other objects, and could push our knowledge farther out in space and time.

The opening of the radio window made the 1960s the golden decade for astronomy, with the discovery of the microwave background and of pulsars. The third great discovery made in that decade was that of quasars (Chapter 23). The term "quasar" originally stood for "quasi-stellar radio source." In fact when an optical telescope is pointed towards the direction of these radio sources, which can be as extended as minutes of arc in radio maps, the resulting optical plate shows a source which looks like a star, that is, an unextended, or "pointlike" object. This apparently innocuous point is instead a gigantic energy plant, able to produce much more power than an entire galaxy like our own, in a volume which is extremely small, if compared with the dimension of the Galaxy, and comparable with our Solar System. The process that powers the stars, thermonuclear reactions, is not efficient enough to power quasars. We believe that at the core of these sources there is a massive black hole, with a mass between a million and a billion that of the Sun. Matter around the hole is attracted by the black hole gravity, it is compressed, heated, and then it radiates. This was realized quite early (Salpeter 1964; Zeldovich 1964; Lynden-Bell 1969; Shakura and Sunjaev 1973).

Another major advance came with the opening of the X-ray window, first (in the 1960s) with rocket experiments pioneered by Riccardo Giacconi, Bruno Rossi, and others, and then with the first X-ray satellites in the early 1970s. The Uhuru, Ariel 5, HEAO 1 and then Einstein satellites made clear that all kinds of quasars were strong X-ray emitters: at the same time, it started to be believed that quasars were perhaps the major contributors to the cosmic diffuse X-ray background, already discovered in 1962 (Giacconi *et al*. 1962).

A third qualitative "jump" was the improvements of the interferometric technique in the radio band, again in the early 1970s. Radio telescopes in different continents, looking at the same source, can resolve details as close as a few tenths of a millisecond of arc. This enabled us to discover that some radio-emitting quasars have spots of radio emission which are observed to move. Sometimes this motion corresponds to velocities that exceed the speed of light. Far from challenging special relativity, this "superluminal" motion, as it is now called, was even predicted before it was observed, by Martin Rees in 1966, and corresponds to real fast motion (but slower than the velocity of light!) at an angle close to our line of sight.

The fourth advance came with the Compton Gamma Ray Observatory (CGRO, launched in 1991) which discovered that the subclass of quasars called blazars are very strong γ-ray emitters, producing at energies greater than 100 MeV more power than in the rest of their electromagnetic spectrum. The properties of blazars are very extreme, and we believe that this is partly due to special relativistic effects because their emitting plasma is moving with a bulk motion at large ($\upsilon \geq 0.99c$) speeds. Blazars and gamma-ray bursts are indeed the realm of special relativity: effects that

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were of academic interest up to 10 years ago suddenly became the keys to understand their behavior.

The discovery of quasars and blazars literally opened up the scale at which we can see the Universe, since they are so powerful that they can be easily seen up to great distances. For 30 years quasars were the most distant known objects in the Universe. And studying these sources we study the effects of both general and special relativity, that is, how space and time change as measured in different frames.

BL LACERTAE OBJECTS AND BLAZARS

The "strange star" BL Lacertae

The star BL in the constellation of Lacertae had been known for many years from its optical variability. When the radio source VRO 42.22.01 was associated with it, people thought they had discovered the first radio star. But unlike other stars, its optical spectrum was completely featureless and this puzzled astronomers. Lots of other things were peculiar about BL Lacertae. The shape of its spectrum did not look thermal, but it was a power law (that is, $F(\nu) \propto \nu^{-\alpha}$). In addition, the optical light was highly polarized, and a high degree of polarization was taken as the signature of synchrotron emission, produced by ultrarelativistic electrons spiraling along magnetic field lines. A lot of observing time was invested in this source to obtain deeper images and spectra. In the end weak absorption lines were observed, from which a redshift of $z = 0.07$ was obtained (Oke and Gunn 1974; Miller and Hawley 1977). This established that BL Lacertae was not a star after all, but a type of quasar.

After the discovery of this prototype, other "stars" were found with similar characteristics, which were named "BL Lacertae objects," or "Lacertids" (or "BL Lacs" for short). At the same time, it was realized that other radio sources, showing the broad emission lines of typical quasars, were also extremely variable in the optical and were named OVVs (optically violent variables) because of this. Their optical spectrum does not generally show the flattening towards the UV indicating the presence of the thermal component due to the blue bump (the thermal emission from the accretion disk) and is therefore non-thermal in origin. Another class of radio-loud quasars, the HPQs (high polarization quasars) showed polarization at a level greater than 3%, and it was finally realized that HPQs were also optically variable, that is, OVVs and HPQs were the same class. It was then found that both BL Lacertae objects and HPQs have a flat radio spectrum, at least at high frequencies, above 1 GHz. These similarities led to the definition of the general class of *blazars* (contraction of BL Lacs and radio quasars). At this time (the 1980s) the LPQs (low polarization quasars) were left out, according to the belief that the polarization characteristics were peculiar and important. But this belief became progressively weaker, up to the discovery of the (often dominant) γ-ray emission in both blazars and LPQs. Then LPQs joined the class of blazars in the 1990s. Linear polarization in the radio band, when observed, is an important tool to diagnose the absence of any cold electron component: if present, these electrons could depolarize the flux due to Faraday rotation of the polarization angle (Wardle 1977). This argument does not apply in the case of electron and positron pairs (they make the polarization angle rotate in opposite directions, and the depolarization effect cancels out).

All blazars so far can be classified as radio-loud objects, but the level of radio emission, with respect to the optical, varies widely. In fact objects selected through X-ray surveys (Extended Medium Sensitivity Survey (EMSS) (Wolter *et al.* 1991), the Einstein SLEW survey (Perlman *et al.* 1996), and the Rosat All Sky Survey (RASS)) can be considered as radio weak, since they have a ratio between the radio flux and the X-ray or optical flux much smaller than the blazars found in radio surveys.

To classify a source as a blazar is not an easy task. There is, however, a useful theoretical definition: There are sources characterized by a relativistic jet producing non-thermal radiation. This radiation is Doppler boosted along the velocity direction, coincident with the jet axis. We call *blazar* a source whose non-thermal radiation dominates over the isotropic components (for example, thermal emission from the accretion disk and nonthermal radio emission from extended regions).

Observationally, we have the following properties of blazars:

- Rapid variability – The flux of all blazars varies violently, with large amplitudes in short times. Variations of a factor of two in hours are common at X- and γ-ray energies, slightly smaller variations are seen in the optical in a single night. Some objects have varied by more than two orders of magnitude over a few years. There are many types of variability: there are objects whose flux varies continuously at all frequencies, without any quiescent phase. There are other objects undergoing violent outburst phases from normally quiescent states. Therefore, if an object is not continuously monitored for a long time, it may be difficult to detect its violent variability.
- Emission at all wavelengths – Blazars are active emitters all across the electromagnetic spectrum, from radio to γ-rays. If we plot the quantity νF_ν *versus* ν their spectrum is characterized by two very broad humps. The peak energies are located in the IR–soft X-ray band and in the MeV–GeV (and even TeV) bands, respectively.

- Non-thermal continuum – Most of the emission (and power) has a power-law shape in restricted energy ranges (a mere decade or so), with weak or absent blue bump.
- Flat radio spectrum – All known blazars, above 1 GHz, have a flat radio spectrum dominated by the core of the jet.

JETS AND FAST MOTIONS

We are now used to seeing beautiful radio maps which can "zoom" in a radio source from the megaparsec to the parsec scale, showing a jet which remains collimated at all scales. Often there are lobes and hot-spots of more intense radio emission at the ends of the jets. There the energy accumulates through million of years, and only a small part of it is radiated away, the rest is used to make the lobe grow and advance in the intergalactic medium.

In the beginning, it was not clear at all how the energy could be transported from the very small center of radio galaxies to regions million of light years away. Then Martin Rees, in his PhD thesis (1966), made the suggestion that this job could be done by matter moving relativistically in a jet. The spectacular prediction he made, out of his idea, was superluminal motion: blobs of radio-emitting matter apparently moving at a velocity greater than the light speed.

Five years later, with the completion of the first Very Long Baseline Interferometry (VLBI), superluminal motion was indeed observed in the blazar 3C 279 (Figure 1; Whitney *et al.* 1971).

Soon after the discovery of the superluminal motion in 3C 279, 3C 273, and other sources, alternative theories were challenging the idea of Rees. One of the most debated was the so called "Christmas tree" theory: different regions of the source light up at different times, giving us the (false) impression of motion. But observations made it clear that what was observed was always a motion from the center to the outer parts of the source, while the "Christmas tree" model predicts also contraction "motions." Furthermore, if the source is moving relativistically, then its radiation is beamed in the direction of motion, as described below, and we indeed have strong evidence for such beaming.

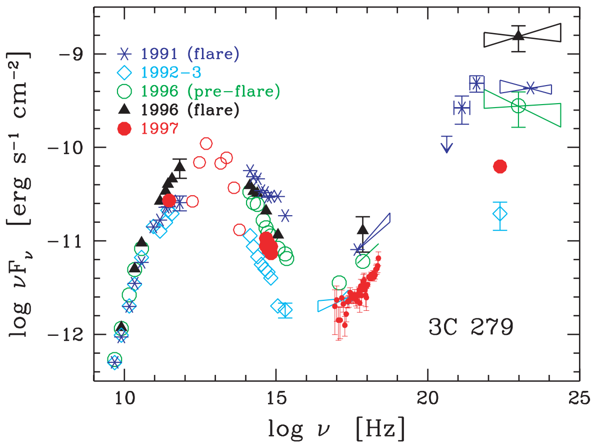

Figure 1 The spectrum of 3C 279 at various epochs. Note the extremely variable flux at all energies, particularly in the CGRO band (0.1–10 GeV). (Adapted from Wehrle *et al.* 1998 and Maraschi *et al.* 1998.)

Superluminal motion

According to the now accepted explanation of superluminal motion, the apparent speed $\beta_{app} = c\upsilon_{app}$ of the radio blobs which are observed to move is due to a projection effect. Once the constancy of the speed of light is accepted, superluminal motion can be explained by simple geometry, with no further involvment of special relativity.

The key point is that the source, while emitting photons, is moving towards the direction of the observer. Suppose we take two maps of the same radio source, separated by a time interval Δt_{obs}. When the source emits the photons of the first map, it is located at the position A (Figure 2). After a time Δt_{em}, the source is located at B. The segment AB $= c\Delta t_{em} - \beta c\Delta t_{em}$, and the distance of the two light fronts in the direction of the line of sight is HC $= c\Delta t_{em} - \beta c\Delta t_{em}\cos\theta = c\Delta t_{em}(1 - \beta\cos\theta)$. This translates to a time interval $\Delta t_{obs} = \Delta t_{em}(1 - \beta\cos\theta)$. The two maps show the "blob" in two different positions, whose projected distance, HB, is $\beta c\Delta t_{em}\sin\theta$. We then obtain $\beta_{app} = \beta\sin\theta/(1 - \beta\cos\theta)$. For small viewing angles (a few degrees) and for relativistic speeds ($\upsilon \sim c$), β_{app} can be greater than c.

Definition and importance of beaming

It is believed that in blazar jets the plasma is flowing with a bulk speed βc close to the speed of light. In terms of the

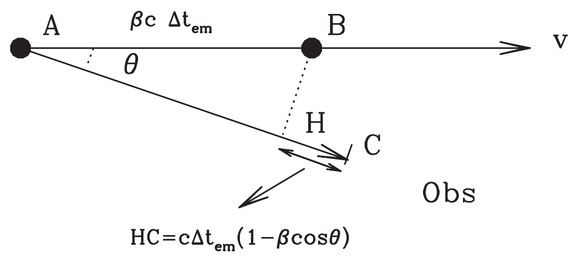

Figure 2 Explanation of the observed superluminal motion. When in A, a "blob" emits a photon. After a time Δt_{em}, the source is in B and emits a second photon. The two photons are separated by HC $= c\Delta t_{em}(1 - \beta\cos\theta)$ and arrive at the observer separated by a time interval $\Delta t_{obs} = \Delta t_{em}$ $(1 - \beta\cos\theta)$.

corresponding Lorentz factor, $\Gamma \equiv (1-\beta^2)^{-1/2}$, we derive values between 5 and 20. Therefore it is essential, in studying blazars, to take into account relativistic effects, the most important of which is called the *beaming* effect. This is the sum of three effects:

(1) Assume that in the frame co-moving with the plasma, the radiation is emitted isotropically. Then half of the photons are emitted in the forward directions, half in the backward directions. An observer, however, sees the plasma moving and so will see that half of the photons are contained in a cone of semi-aperture angle equal to $1/\Gamma$. This is due to the aberration of light.
(2) Since the source of radiation is moving, we must take into account the change of frequency of the observed photons (Doppler effect).
(3) The rate of arrival of photons is not equal to the rate of emission, as measured in the co-moving frame (if we run towards a source, we will collect more photons per second than if we do not run).

These three effects also depend on the angle between our line of sight and the velocity vector of the plasma. They conspire to make the emitting source much brighter if we see it at small viewing angles (photons are concentrated in this small solid angle, they are seen blueshifted, with an enhanced rate of arrival), and much dimmer at large viewing angles. Therefore the (frequency integrated) intensity I of a moving source depends both on its velocity and the viewing angle: $I = \delta^4 I'$ where I' is the intensity seen by a co-moving observer, and $\delta \equiv 1/[\Gamma(1-\Gamma\cos\theta)]$ is the so called Doppler boosting factor. We can see that the intensity can be enhanced by orders of magnitudes when θ is small (a few degrees) and $\beta \sim c$.

Note that relativistic motion greatly affects the variability timescales we measure. Suppose that in the co-moving frame the source flares in a time $\Delta t'$. According to special relativity, this time would be seen, at Earth, longer by a factor Γ. But this is true *only if we do not use photons* to measure this time! If instead we do, then we must take into account that the source has emitted the first photons when it was located in a certain region, and the last photons when it was located *in another position*. Therefore the two bunches of photons traverse paths of different length to reach us. This is the Doppler effect, and contributes a factor $1-\beta\cos\theta$. The two effects combine to give $\Delta t = \Delta t'\Gamma(1-\beta\cos\theta) = \Delta t'/\delta$: for small viewing angles the observed time is *shorter*, not longer!

The enhancement of the observed radiation by beaming can be tested through the following argument. If one assume that the radio emission, as mapped by VLBI techniques, is produced by the synchrotron process in a stationary source, then one can calculate how many electrons are needed to produce the radio emission we see. Knowing directly the size by VLBI, one derives the particle and the photon densities. Therefore one can estimate the probability of interactions between synchrotron photons and relativistic electrons, predicting the flux at high energies, especially in the X-ray band. These estimates often turn out to be orders of magnitude greater than observed. If we now assume that instead the source is moving towards us at relativistic speeds, the fluxes we receive are enhanced, therefore less electrons are needed to produce this emission, and the calculated photon density at the source is lower. The interaction probability is less than before. The estimate of the X-ray flux then depends on the Doppler factor: by matching the predicted X-ray flux with the observed flux we can put an upper limit to the amount of beaming. It is an upper limit because the radio region we are observing at the VLBI may not be the only contributor to the X-ray flux.

Radiation processes

In tenuous plasmas interactions between particles (which depend on their density) are not efficient in sharing the energy between the particles. If the injection of energy is due to the acceleration of few ultrarelativistic particles, then the particle distribution has no chance to become thermal (that is, described by a Maxwellian distribution). In rarefied relativistic plasmas the most efficient ways to produce radiation are the synchrotron and the inverse Compton processes. The first depends on the strength of the magnetic field, the second on the density of the seed photons to be scattered. When these seed photons are produced by the synchrotron process the resulting mechanism is called the synchrotron self-Compton process. For 20 years this was thought to be the main mechanism responsible for the observed radiation, from the radio to the X-ray band, until the high-energy γ-ray emission was discovered (e.g. Ginzburg and Syrovatskii 1965; Rees 1967; Blumenthal and Gould 1970; and Jones *et al.* 1974a,b). The origin of the high-energy γ-ray emission is still controversial, since the contribution of radiation produced externally to the jet is enhanced by the bulk motion (see below) and can overtake the locally produced synchrotron radiation as a producer of seed photons to be scattered (Maraschi *et al.* 1992; Dermer and Schlickeiser 1993 Sikora *et al.* 1994; Blandford and Levinson 1995; Ghisellini and Madau 1996). It is also fair to mention that even the inverse Compton nature of the γ-ray emission is controversial: as Mannheim (1993) suggested, it could be due to the synchrotron process, due to an additional population of ultrarelativistic electrons as a result of photon–meson interactions. Independent of its nature, the high-energy emission (in the X- and γ-ray bands) firmly established the need for relativistic bulk motion.

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