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Simultaneous multifrequency observations of blazars(*)(**)

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Summary. — Among active galactic nuclei, blazars have the most highly and rapidly variable spectral continua at all the wavelengths. Their repeated observation at different energies allows therefore to investigate the geometry and the physics of the emitting regions, provided the multifrequency data are monitored simultaneously and with complete and frequent sampling, to allow a reliable correlation analysis of the light curves at different wavelengths. The coordinated efforts of several international astronomical groups toward multifrequency monitoring implementation allowed to obtain unprecedentedly high quality data and to achieve substantial improvement in the theoretical understanding of the blazars PKS 2155–304 and 3C 279.

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1. – The blazar phenomenon

Blazars are extremely active galactic nuclei, radiating bolometric luminosities of even 10^{48} erg s^{-1} (from radio to γ-rays), and exhibiting rapid and large flux variability at all frequencies, with total luminosity variations $\Delta L/\Delta t$ in excess of the fiducial limit for Eddington-limited accretion with efficiency η=0.1 (Fabian, 1979). According to whether line emission is strong or weak (equivalent width $\lesssim 5$ Å) in these sources, they are classified as Optically Violently Variables (OVV), or BL Lacertae Objects (BL Lacs). However, recent agreement has developed that OVV and BL Lacs form two intrinsically different populations (see, *e.g.*, Urry and Padovani, 1995). The high luminosities, the compact radio cores, the observed superluminal motions and the fast, high-amplitude time variability suggest that beaming is present in blazars, a hypothesis which is confirmed by the absence of the *Compton catastrophe* (Kollgaard 1994, and references therein). The polarization of

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the blazar emission and the power law shape of the radio-to-X-ray spectra of these objects favor the synchrotron radiation mechanism as responsible for the continuum production from radio to X-ray frequencies. If the electrons are accelerated by magnetic fields within an elongated structure (jet) originating from the inner powerful nucleus, and the direction of the jet forms a small angle with the observer's line of sight, the emitted energy is relativistically boosted along the jet, thus the observed luminosity appears enhanced by a quantity depending on the bulk Lorentz factor Γ of the relativistic plasma and on the viewing angle. Flux variations can be relativistically affected as well, thus the effect of the jet orientation must be taken into account when evaluating linear sizes of the emitting regions from variability time scales. The jet-like geometry for blazars gave rise to several theoretical models for the emission (see the review of Bregman, 1990). One of the most accredited pictures is the inhomogeneous jet model (Ghisellini *et al.*, 1985), where the emitting region is made up of a paraboloid ending up in a cone. The relativistic plasma flow accelerates outwards in the parabolic part of the jet (Ghisellini and Maraschi, 1989). In this model, the overall spectrum is the sum of the local contributions which have different spectra. Energetically, the dominant emission region is the outer part of the paraboloid, while the conical region, smoothly connected to the internal one, is necessary to account for the radio emission. In this scenario, the observed blazar variability, of higher amplitude and shorter time scales at decreasing wavelengths, is suitably explained through a shock moving down the jet (Celotti *et al.*, 1991).

2. – The broad-band energy distribution of blazars

Single epoch, simultaneous multifrequency observations of blazars allow to construct spectral flux distributions over an extended energy range and to evaluate the overall spectral slope. It is crucial that monochromatic fluxes, measured by different instruments, are taken strictly close in time; otherwise, possible temporal flux variations can result in unreal colour changes and then cause spurious spectral breaks or features. The variability time scales in blazars range from few hours (X-rays) to months or years (radio and infrared wavelengths), thus the simultaneity requirement depends on the observing energy band. Time separations of ~ 1 day between observations at different wavelengths are needed to avoid variability effects of unphysical nature in the infrared-to-ultraviolet spectral region. A study of 11 BL Lacs in this spectral band ($8{\cdot}10^{13}$–$2{\cdot}10^{15}$) Hz, (Pian *et al.*, 1994) was based on the data obtained during a 10 year program of quasi-simultaneous observations at ESO, at near-infrared and optical frequencies, and with the IUE satellite, whose SWP and LWP cameras are sensitive to the far-ultraviolet light. For all the objects except one, after proper correction of the data for interstellar extinction and subtraction of the stellar contribution due to the host galaxy of the active nucleus, the spectrum is well described by a single power law $F_\nu \propto \nu^{-\alpha_\nu}$, of average index $\langle\alpha\rangle = 1$. A marked tendency is seen for radio-weak objects to be "flatter" (*i.e.* to have smaller spectral indices) than radio-strong ones, which is related to a different beaming angle in the two classes (see Maraschi *et al.*, 1986). The absence of breaks or curvature in the spectral shape suggests that a single mechanism (synchrotron radiation) taking place within a unique emitting volume is responsible for the emission in the studied energy range.

The high-energy part of the blazar spectrum (≥ 1 keV) is likely produced by inverse Compton scattering of relativistic electrons off the synchrotron photons themselves (synchrotron-self Compton process (SSC) see, *e.g.*, Maraschi *et al.*, 1992) or on ambient photons, such as those present in the accretion disc surrounding the central supermassive blackhole or in the broad-line region clouds (external Compton, see, *e.g.*, Dermer and Schlickeiser, 1993; Sikora *et al.*, 1994). In the inhomogeneous model scenario, the rising soft and medium energy X-ray spectra seen in several radio-strong blazar objects (Sambruna *et al.*, 1994) represent the result of SSC radiation produced by scattering of electrons off radio photons, whereas scattering of the relativistic particles off infrared, optical and ultraviolet light should be responsible for the MeV and GeV energy part of the spectrum. The recent detection of blazars in the γ-rays (30 MeV–20 GeV) by the EGRET instrument onboard the satellite GRO confirmed this relation between the two emission processes, since the broad-band energy distributions of the γ-ray emitting blazars show two humps (see also Maraschi *et al.*, 1994a; Pian *et al.*, 1996) of similar shape and peaked, respectively, at $\sim 10^{13}$ Hz (infrared) and $\sim 10^{21}$ Hz ($\sim$ 1 MeV) for the radio-strong objects, or at $\sim 10^{16}$ Hz (extreme ultraviolet) and $\sim 10^{24}$ Hz ($\sim$ 1 GeV) for the radio-weak objects, the "shift" in frequency between the two classes being due to a different beaming factor.

3. – Variability of blazars

Blazars are characterized by a remarkable emission variability at all the wavelengths. The flux variations, which are either recurrent or occasional (isolated flares) are generally of larger amplitude and shorter time scales at decreasing wavelengths (see, *e.g.*, Bregman, 1990). In the framework of the inhomogeneous jet model, the higher-frequency radiation is produced closer to the innermost source. It thus reflects the extreme energetic conditions present in this restricted and compact region, and its variability is then characterized by larger amplitude and shorter time scales than that of the lower frequency emission, produced further out in the jet. Rapid fluctuations are most likely to contain information about the size of the inner power-house, while slower variations are dominated by radiative cooling or heating, or slow changes in the structure of the system. Spectral changes are usually smaller than flux variations in all bands, as deduced from observations in the radio/millimeter (Gear *et al.*, 1994), near-infrared (Massaro *et al.*, 1994), optical (Falomo *et al.*, 1994), ultraviolet (Edelson 1994, and references therein) and X-ray domains (Sambruna *et al.*, 1994); moreover they are not obviously correlated with flux (see below the case of PKS 2155-304). The relative stability of the spectral slope in blazars despite the remarkable flux changes suggests that the emission in a given energy band is dominated by a single component (Edelson 1994). A possible alternative explanation relies in considering these objects as gravitationally lensed background quasars.

The blazar broad-band variability can be investigated through repeated multifrequency observations, to add temporal information to the spectral and flux characteristics. Variability monitoring at all the frequencies from radio to γ-rays has been proven to be invaluable in understanding the continuum processes as well as the geometry of the innermost regions in these objects. Although sizes can be determined directly from VLBI observations in the radio region, the central engine is much too small to image from Earth, thus the only tool for probing the source structure is the temporal evolution of its spectrum. Furthermore, the correlation analysis of monochromatic light curves at different frequencies provides insight to the causal link between the emission components and allows to test the theoretical models on blazar radiation.

Repeated simultaneous observations at different energies require a continuous and regular monitoring (*i.e.* without time gaps in the total observing duration) with frequent sampling, to avoid a spurious "mismatch" between fluxes in different bands due to short-term variations (see sect. 2) and to resolve small flares due to extremely short-term variability (microvariability). Therefore, the organization of simultaneous multiwavelength campaigns is based on the collaboration of several research groups coordinating the observing facilities (ground- and space-based instruments), to guarantee a coverage of the entire electromagnetic spectrum, and a regular and intensive sampling at all the studied frequencies.

4. – Multifrequency observational programs

Previous multifrequency blazar monitorings have been realized with the aim of studying the evolution of the broad-band spectral energy distribution (*e.g.*, PKS 2155-304, Treves *et al.*, 1989, and references therein; OJ 287, Pian *et al.*, 1995; PKS 0716+714, Wagner 1992; Mkn 421, George *et al.*, 1988). In most of these campaigns the temporal sampling and multiwavelength coordination were insufficient to allow determination of the temporal correlation and lags between the bands. Recently, the IUE, EUVE, ROSAT, ASCA and GRO satellites for the astronomical research at the high and very high energies were simultaneously scheduled, often in conjunction with radio and optical telescopes, for intensive blazar monitoring programs.

In the recent past years, two important sources were selected for simultaneous multifrequency campaigns: PKS 2155-304 ($z = 0.116$), a typical X-ray selected BL Lac and the brightest extragalactic object in the ultraviolet band —which makes it a particularly suitable IUE target— and the OVV quasar 3C 279 ($z = 0.538$), a luminous and variable radio-strong source, and the most powerful γ-ray emitter among the extragalactic objects detected by GRO. The main results of these observing campaigns will be discussed in the following sections.

5. – PKS 2155-304

The object was intensively monitored on two occasions. The first monitoring campaign, based on the coordination of the IUE and ROSAT satellites operations, took place during November 1991 and was mainly aimed at investigating the typical variability time scales of the optical/ultraviolet emission and its correlation with the soft X-ray flux. IUE observations with the SWP (1000-2000 Å) and LWP (2000-3000 Å) cameras and with the FES used as optical photometer (5000 Å) were programmed with a schedule of at least one shift (8 hours) per day along the month plus 4.6 days of intensive uninterrupted monitoring (3 shifts per day from November 10 to 15). A total of 200 ultraviolet spectra and as many FES counts were obtained, which have been reduced, analysed and discussed by Urry *et al.* (1993). During 3 days, simultaneously with the five days interval of intensive IUE coverage, ROSAT observed continuously the source with the PSPC (0.1–2.4 keV), collecting $\sim 10^6$ photons (Brinkmann *et al.*, 1994). Simultaneous radio and near-infrared observations were secured together with optical spectroscopy and UBVRI photometry and polarimetry (see Smith *et al.*, 1992; Courvoisier *et al.*, 1995).

The unprecedented coverage obtained at the far-ultraviolet wavelengths through the IUE monitoring with both working cameras yielded light curves at 1650 and 2600 Å which appear very well correlated with each other (fig. 1a)) and with the FES optical light curve (see fig. 2). On the overall flux doubling, smaller amplitude variations are overimposed with a time scale of $\sim$1 day. The absence of a measurable lag between the ultraviolet and optical radiation strongly favors the synchrotron mechanism as responsible for its production, ruling out a thermal process, such as emission from an accretion disc, since in this case the ultraviolet emission would lead the optical by at least some days. The correlation analysis of the ultraviolet light curves with the ROSAT light curve shows that

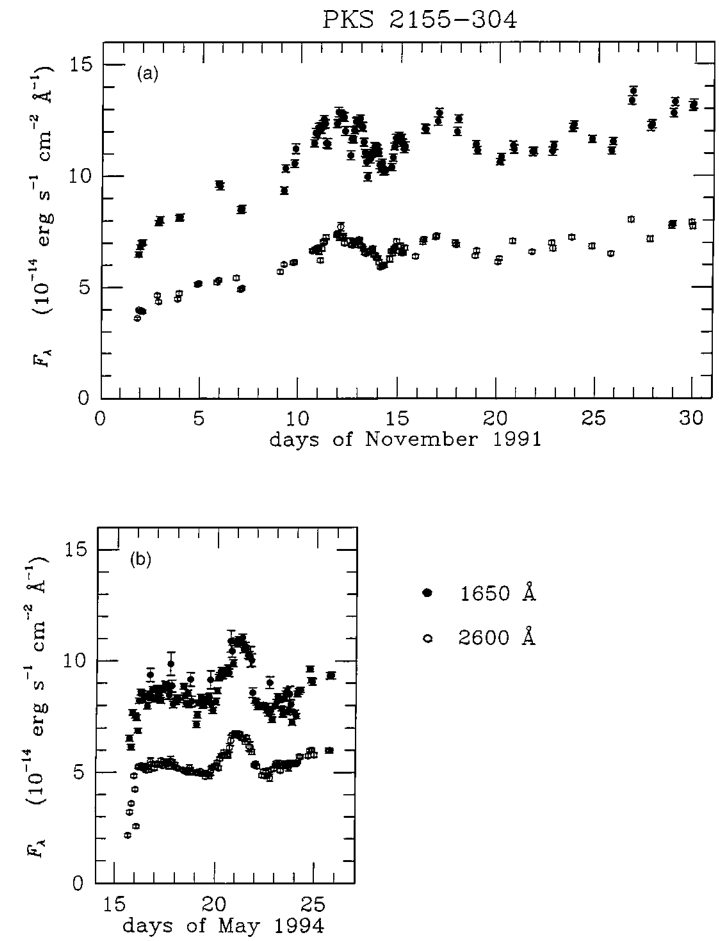

Fig. 1. – a) IUE light curves of PKS 2155-304 from the 1991 November campaign and b) from the 1994 May campaign.

they are still well correlated, and of similar shape, but the former lag the X-rays by ~ 2 hours (Edelson *et al.*, 1995). This supports the interpretation that the soft X-ray emission is produced through synchrotron radiation as well, and it is not due to the inverse Compton process, otherwise it could not lead the lower-frequency emission. The observed lag between X-ray and ultraviolet emission (~ 2 hours) is considerably shorter than the variability timescale (~ 1 day), which implies *in situ* reacceleration of relativistic emitting particles and is accounted for by synchrotron emission originating within a shock front moving down the jet. The absence of remarkable spectral variability in the single ultraviolet and X-ray bands and the correlated achromatic variations in these domains confirm the presence of a unique component as responsible for the high-frequency emission in this blazar object.

During the second multifrequency campaign on PKS 2155-304, conducted in May 1994, the IUE instruments (SWP and LWP cameras only) were scheduled for a shorter period (10 days) than earlier, but with continuous daily coverage, which represented an

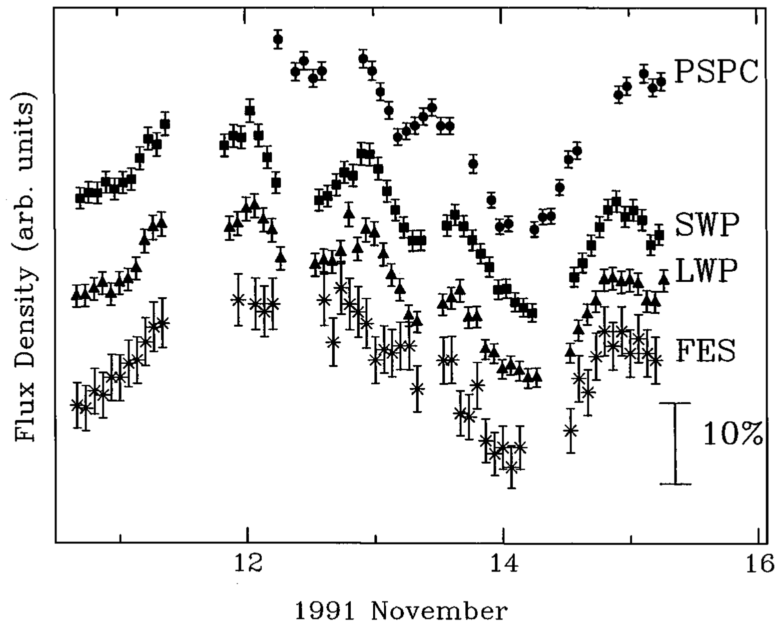

Fig. 2. – Optical, ultraviolet and soft X-ray light curves of PKS 2155-304 from the 1991 November campaign during the intensive coordinated IUE and ROSAT monitoring period (from Edelson *et al.*, 1995).

unprecedented opportunity in blazar monitoring at ultraviolet wavelengths. A comparably frequent sampling was simultaneously obtained at the extreme ultraviolet energies with the EUVE (Marshall *et al.*, in preparation) and, for a shorter time interval, with the hard X-rays ASCA satellite (Kii *et al.*, in preparation). The HRI instrument onboard ROSAT also observed the object in three occasions along the monitoring (Madejski *et al.*, in preparation). The aim of the coordinated IUE, EUVE, ROSAT and ASCA campaign was to resolve very short-term high frequency variability, and to test the correlated optical/ultraviolet and X-ray variability. Ground-based instruments observed simultaneously the source at radio, millimeter and optical frequencies, to provide information on the lower-frequency part of the spectral continuum (Pesce *et al.*, 1997). The IUE light curves (fig. 1b)) are well correlated with each other without any measurable lag, and of completely different appearance than in the previous campaign, showing an impressive flaring trend in the very first part, were the flux doubles in a time interval comparable with the IUE cameras exposure time (Pian *et al.*, 1997). The correlation of the IUE and EUVE light curves appears good, with a lag of the former with respect to the latter of more than 1 day. The correlation of the two well sampled, hard X-ray light curves obtained with the ASCA instruments SIS (0.5-7 keV) and GIS (0.7-8 keV) is good. The far- and extreme-ultraviolet, and the X-ray light curves exhibit a big flare, which is more rapid and of higher amplitude at the shorter wavelengths. If the IUE and ASCA detected outbursts are correlated, then the former lags the latter by almost two days (Urry *et al.*, 1977). Therefore, if the emission process responsible for high-energy emission in PKS 2155-304 is non-thermal, as established from the previous campaign, then the hard X-rays are produced, like optical, ultraviolet and soft X-rays, by synchrotron radiation, and not by SSC. The synchrotron

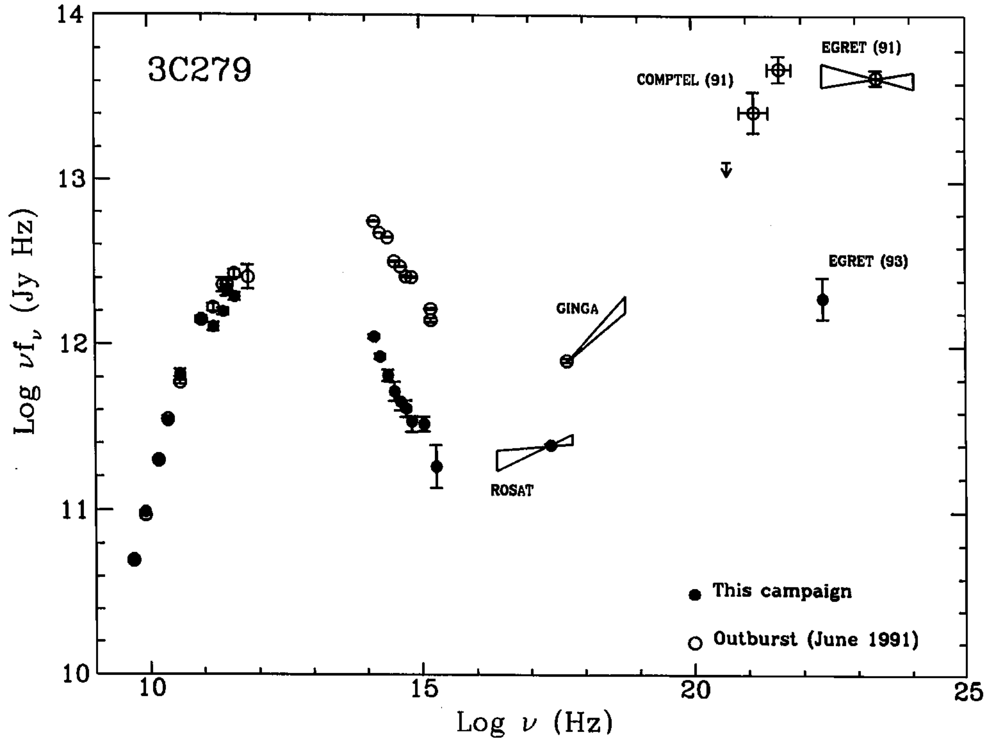

Fig. 3. – Radio-to-γ-ray energy distribution of 3C 279 as derived from the quasi-simultaneous observations from 1992 December to 1993 January. Data referring to 1991 June, mostly taken from the literature, are shown for comparison. The COMPTEL upper limit refers to the 1991 observation (from Maraschi *et al.*, 1994b).

emission component peaks in this source in the extreme-ultraviolet region of the spectral energy distribution (Edelson *et al.*, 1995), and extends up to ~ 10 keV, implying extremely energetic particles. The inverse Compton component will therefore probably peak at ~ 1 GeV, as suggested also by the γ-ray photon index ($\Gamma_\gamma = 1.69 \pm 0.26$) recently measured by GRO in the energy range 30 MeV-10 GeV (Vestrand *et al.*, 1996).

Since the wavelength dependence of the flare amplitude and the 1-2 day lag observed in the second campaign are in sharp contrast to the results from 1991 multiwavelength monitoring, which showed optical, ultraviolet and X-ray light curves varying with the same amplitude and with a shorter lag (2-3 hours), it has also been suggested that the two kinds of variability must have different explanations. The 1994 data are qualitatively consistent with a synchrotron flare from a propagating shock in a relativistic jet, while it may be possible to explain the achromatic variations seen earlier by gravitational microlensing (Urry *et al.*, 1994).

6. – 3C 279

According to the inhomogeneous model, the γ-ray emission from blazars originates from inverse Compton scattering of relativistic electrons off the optical and ultraviolet photons, therefore the flux and spectral variability at those energies are expected to be correlated. A general property of the SSC model is that, when the electron distribution decreases in number, the synchrotron luminosity decreases proportionately, while the inverse Compton luminosity decreases quadratically (Maraschi *et al.*, 1992). If, instead, the photon energy density as seen in the jet frame is dominated by external photons, when the electron spectrum varies, the synchrotron and inverse Compton emission components will both scale proportionately. The detectability of γ-ray flux variability in 3C 279 makes this source an ideal laboratory to test the two different predictions.

Simultaneous observations at radio, millimeter, near-infrared, optical, ultraviolet (with *IUE*) and X-ray (with *ROSAT*) wavelengths were obtained in 1992 December-1993 January, during a three-week pointing at the source by *GRO* (Maraschi *et al.*, 1994b). The blazar was in a quiescent state in this period. Comparing the multiwavelength energy distribution to that from 1991 June (fig. 3), when 3C 279 was in its brightest recorded γ-ray state, it has been found that it faded dramatically at all frequencies above 10^{14} Hz, while the flux variations at low frequencies (radio-to-millimeter wavelengths) were minor, so that the ratio of the γ-ray luminosity to that across all other frequencies decreased from a value of ~ 10 in the flaring state to a value of ~ 1 in the quiescent state. Hence, the energy distributions of 3C 279 in high and low state are consistent with the SSC model, since the γ-ray luminosity, assumed to represent the inverse Compton luminosity, varies by a larger factor than the observed synchrotron luminosity. The observed nonlinear relation between the synchrotron and inverse Compton requires both a change in the electron spectrum and an associated change in the seed photons.

7. – Conclusion

The success of the recent blazar monitoring campaigns relies on the endeavour of international collaborating groups to simultaneously coordinate the observing facilities. In order to maximize the scientific output and rigorously test the models, it is crucial to have complete information over the whole electromagnetic spectrum from radio to γ-ray energies, and to obtain frequently, regularly sampled light curves. The two examined sources were excellent examples where the accomplishment of such multiwavelength study led to fundamental results. In both cases the variability at different frequencies was an important test for the inhomogeneous model, which appears a good candidate for the correct interpretation of the blazar continuum emission. The quality of the observations can however put some important additional constraints to the model contributing to improve it. The selected sources, bright and variable, will be good targets for the satellites which will start their space mission in the next future, ISO and SAX. Due to their extended wavelength observing range, they will be able to provide very precise information on the spectral shape variability, and on its possible correlation with flux, which is a critical issue in investigating blazars. Therefore, these new space resources will be particularly well-suited for blazar monitoring.

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