

# Optical monitoring of Active Galactic Nuclei from ARIES

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**Abstract:** This overview provides a historical perspective highlighting the pioneering role which the fairly modest observational facilities of ARIES have played since the 1990s in systematically characterizing the optical variability on hour-like time scale (intra-night optical variability, or INOV) of several major types of high-luminosity Active Galactic Nuclei (AGN). Such information was previously available only for blazars. Similar studies have since been initiated in at least a dozen countries, giving a boost to AGN variability research.

Our work has, in particular, provided strong indication that mild INOV occurs in radio-quiet QSOs (amplitude up to  $\sim 3 - 5\%$  and duty cycle  $\sim 10\%$ ) and, moreover, has demonstrated that similarly mild INOV is exhibited even by the vast majority of radio-loud quasars which possess powerful relativistic jets (even including many that are beamed towards us). The solitary outliers are blazars, the tiny strongly polarized subset of powerful AGN, which frequently exhibit a pronounced INOV. Among the blazars, BL Lac objects often show a bluer-when-brighter chromatic behavior, while the flat spectrum radio quasars seem not to. Quantifying any differences of INOV among the major subclasses of non-blazar type AGNs will require dedicated monitoring programs using 2 – 3 metre class telescopes.

## 1 The groundwork

The epochal discovery of quasars (Schmidt 1963) was quickly followed by the intriguing announcement of optical microvariability of the quasar 3C 48 by  $\sim 4\%$  over just 15 minutes (Mathews & Sandage 1963). In the following two decades, similar events of rapid optical variability were reported for a few blazars, the most active subset of Active Galactic Nuclei (AGN), as recounted in Jang & Miller (1997). In hindsight, all these claims of blazar variability seem plausible, although they evoked persistent skepticism until the late 1980s when CCD cameras came to be deployed for intra-night optical monitoring of AGN, allowing simultaneous recording of many (comparison) stars on the same CCD chip. The advantage then is that they all are subjected to essentially the same air mass, weather and instrumental conditions. Hence, any variations due to these factors are effectively cancelled out simply by performing differential photometry between the AGN and stars in the same field-of-view. This mode of using the CCD camera as a multi-star photometer routinely yielded reliable, sensitivity enhanced “differential light curves” (DLCs) of the monitored compact AGN relative to several comparison stars (Miller et al. 1989; Carini et al. 1990; Wagner et al. 1990; Quirrenbach et al. 1991; Carini & Miller 1992; Noble et al. 1997). Such AGN variability was termed optical microvariability and later

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as, intra-night optical variability (“INOV”, see, Gopal-Krishna et al. 2003). It is somewhat amusing that the radio equivalent of INOV of blazars had already been established (Witzel et al. 1986; Heeschen et al. 1987), though in many cases it could be largely due to propagation effects (e.g., Shapirovskaya 1978; Rickett et al. 2001; Jauncey & Macquart 2001; Liu et al. 2011; de Bruyn & Macquart 2015; Gopal-Krishna & Subramanian 1991; also, Vedantham et al. 2017; but see Wagner et al. 1996; Krichbaum et al. 2002; Gabañyi et al. 2007; Wagner et al. 2008).

During the first few years, INOV searches remained focused on prominent BL Lacs, flat-spectrum radio-loud quasars (FSRQs) and Seyferts (e.g., Jang & Miller 1995; see Gopal-Krishna et al. 1995 for a summary). The first step towards diversifying to other major classes of high luminosity AGN was taken by one of us (G-K) in 1991, by taking intra-night ‘snapshots’ of two radio-quiet QSOs (RQQSOs or RQQs) using the New Technology Telescope (NTT). Although neither RQQSO showed INOV (Gopal-Krishna et al. 1993a), we felt motivated to continue this program using the just commissioned 2.34-m Vainu Bappu Telescope (VBT) of the Indian Institute of Astrophysics (IIA). The resulting first paper reported a negative search for INOV in 5 high-luminosity RQQs ( $M_B < -25$ ), down to a 2–3% detection threshold (Gopal-Krishna et al. 1993b). This study, coinciding with G-K’s sabbatical visit to the Space Telescope Science Institute, was in fact the first VBT publication in an international journal (Rao 1995). Our next paper reported densely sampled intranight DLCs of 6 RQQs and one “radio-intermediate quasar” (Gopal-Krishna et al. 1995). Among these RQQSOs, strong hints of INOV (amplitude  $\psi \sim 5\%$ ) were seen in the DLCs of PG 0946+301 ( $z = 1.216$ ,  $M_V = -28.6$ ) and also for PG 1630+377 ( $z = 1.466$ ,  $M_V = -29.5$ ). Additional examples of INOV of RQQs are reported in de Diego et al. (1998). The possibility had been mentioned that such INOV could be associated with transonic flows and shocks within the accretion disk (Chakrabarti & Wiita 1992). Alternative accretion disk origins for INOV include an array of hotspots (e.g., Mangalam & Wiita 1993), disk oscillations (Nowak & Wagoner 1991, 1992), plasma instabilities (Krishan & Wiita 1994). Some other proposals invoke a clumpy torus (Nenkova et al. 2008) or reprocessing of coronal X-ray flares in the accretion disk (e.g., Rokaki et al. 1993; Merloni & Fabian 2001); further possibilities are considered in Wiita (1996) and Raginski & Laor (2016).

In an independent program, Jang & Miller (1997) reported hour-scale micro-variability for two RQQSOs whose luminosities are close to the borderline between QSOs and Seyfert galaxies (cf. Miller et al. 1990). Based on admittedly small samples, both they and we were led to conclude that INOV is distinctly rarer and milder among RQQSOs, as compared to blazars, establishing the inevitability of jet (vis a vis accretion disk) origin for a pronounced INOV. For the jet dominated sources, the strong relativistic enhancements of small fluctuations arising through turbulence (e.g., Marscher & Travis 1991; Romero et al. 2000; Goyal et al. 2012; Marscher 2014; Calafut & Wiita 2015; Pollack et al. 2016), or ultra-relativistic mini-jets (Giannios et al. 2009, 2010; also, Singal & Gopal-Krishna 1985) certainly dominate the short-term variability in blazars across all bands. The geometric explanations for rapid blazar variability include the ‘lighthouse effect’ (Camenzind & Krockenberger 1992) and the ‘swinging jet’ scenario (Gopal-Krishna & Wiita 1992; also, Bachev et al. 2012).

## **2 The transition phase from VBT (IIA) to ST (UPSO) [1996 - 99]**

The transition from the VBT to our new “workhorse”, the 1.04-m Zeiss telescope (the Sampurnand Telescope, hereafter ST) of the Uttar Pradesh State Observatory (UPSO, later ARIES), was a watershed. An update on our INOV program, particularly the INOV patterns of RQQs vs RLQs, is provided in Gopal-Krishna et al. (2000), together with the prevailing international setting which was still in a confused state (see, e.g., Jang & Miller 1995, 1997; de Diego et al. 1998; Rabbette et al. 1998; Romero et al. 1999). As discussed below, this was partly due to the tendency to lump together diverse types of radio-loud AGN (see, e.g., Helfand 2001; Carini et al. 2007; Ramírez et al. 2009). Thus, a systematic characterization of the INOV of major classes of high-luminosity AGN became our focus.

Using the ST, we launched in 1998 a program of R-band intranight monitoring of 7 sets of bright ( $m_B \sim 16$ ) AGNs, each set falling in a narrow redshift bin within the overall range  $z = 0.17$  to 2.2. Each set consisted of a RQQ, a BL Lac (except in the highest  $z$  bin), a radio lobe-dominated quasar (LDQ), and a core-dominated quasar (CDQ). The four major AGN classes in this sample are thus matched in the  $z - M_B$  plane. We monitored each AGN for 4 to 8 hours per night, each on at least 3 nights, taking  $\sim 5$  exposures per hour. This program took

113 nights (720 hours) during 1998–2002. All 7 RQQs are not only very luminous ( $-24.3 > M_B > -29.8$ ) but are also genuinely radio-quiet, with  $R < 1$ , where  $R$  is the rest-frame ratio of 5 GHz to 440 nm flux densities (Kellermann et al. 1994). Normally, intranight variations of 1-2% could be detected in our DLCs.

The first publication from this UPSO program reported INOV of the RQQs B1029+329 ( $M_B = -26.7, z = 0.560$ ) and B1252+0200 ( $M_B = -24.8, z = 0.345$ ), albeit the INOV amplitude ( $\psi$ , defined in Romero et al. 1999), was  $< 3\%$  for all 7 RQQs monitored, unlike the BL Lacs which overshot this limit in  $\sim 50\%$  of the sessions (Gopal-Krishna et al. 2003; see, also Stalin et al. 2004a; Sagar et al. 2004; Carini et al. 2007; Gopal-Krishna et al. 2011). Thus, our data provided, for the first time, an estimate of INOV duty cycle (DC) for BL Lacs in different ranges of  $\psi$ . We further showed that even a violently intranight variable, like the BL Lac AO 0235+164, would exhibit a very low-level INOV (reminiscent of RQQs) were its jet misaligned from the line of sight by just  $10\text{--}15^\circ$ , thanks to the drastic relativistic flux de-boosting and time stretching (Gopal-Krishna et al. 2003; Stalin et al. 2004a; also, Czerny et al. 2007). INOV detections for RQQs were also reported from other observatories (e.g., Gupta & Joshi 2005; Stalin et al. 2005; Ramirez et al. 2009; Polednikova et al. 2016).

The next step of our program was to compare the INOV characteristics of two AGN classes which appear strongly relativistically beamed, CDQs and BL Lacs. For this, matched samples of 5 CDQs and 6 BL Lacs were monitored in 46 sessions, each lasting  $\sim 6.5$  hours (Sagar et al. 2004). This was the first clear demonstration that the presence of even a relativistically beamed radio core is no guarantee of strong (blazar-like) INOV and that a high optical polarization is the critical factor, as amply confirmed by Goyal et al. (2012; see below).

Another novel step in our program was to systematically compare the INOV properties of RQQs and radio lobe-dominated quasars (LDQs). For this, 7 optically bright and high luminosity RQQs and 7 LDQs matched in the  $z - M_B$  plane, were monitored in 61 sessions of  $\sim 6$  hour duration. Once again, contrary to the folklore that INOV correlates with radio loudness, we found that the INOV characteristics ( $\psi$ , DC) of LDQs compare well in mildness with those of RQQs (Stalin et al. 2004a,b). Since LDQs are universally believed to have powerful relativistic jets, our INOV result meant that RQQs need not be devoid of relativistic jets, either. This idea, in fact, accords well with the jet-disk symbiosis hypothesis (e.g., Falcke et al. 1995). More direct support has come from the VLBI detections of radio cores in many RQQs (e.g., Blundell & Beasley 1998; Caccianiga et al. 2001; Ulvestad et al. 2005; Falcke et al. 1996; Leipski et al. 2006; Herrera Ruiz et al. 2016) and from radio flux variability (Barvainis et al. 2005; Wang et al. 2006) and detection of extended radio lobes (Kellermann et al. 1994; Blundell & Rawlings 2001). Likewise, from a detailed analysis of the radio–far-IR correlation, White et al. (2017) have gathered credible evidence for AGN dominated radio flux of many RQQs. Note, however, that Raginski & Laor (2016) have argued that the origin of the VLBI cores in RQQs needs not invoke nonthermal relativistic jets (see also Ishibashi & Courvoisier 2011; Steenbrugge et al. 2011). Reverting to the compact jet scenario, the possibility has been advanced that RQQs may arise from an inverse Compton quenching of the jets in a majority of QSOs, before reaching the physical scale probed by radio emission (e.g., Brown 1990; Barvainis et al. 2005; also, Xu et al. 1999). A possible signature of such quenching is the hard tail seen in the X-ray spectrum of several RQQs above  $\sim 5$  keV (George et al. 2000). Note that detection of such emission is strongly disfavored because of the very narrow pattern of the inverse Compton boosting of external (e.g., broad-line region) photons by the relativistic jet (see, Dermer 1995). Thus, even though the jet scenario for RQQs does not discount starbursts playing a major role in *long-term* optical variability (Terlevich, Melnick & Moles 1987), it does highlight the relevance of INOV studies to the outstanding issue of the QSO radio dichotomy, reviewed, e.g., by Begelman et al. (1984), Urry & Padovani (1995) and Antonucci (2012).

To recapitulate, it has come to be appreciated that radio loudness of a quasar (even if due to a jet relativistically beamed towards us) is not a sufficient condition for detecting a pronounced INOV, as displayed by blazars. *There is no one-to-one mapping of the radio dichotomy of quasars to their INOV properties.* Remarkably, a similar conclusion has been reached from *radio* continuum variability on month-like time scales (Barvainis et al. 2005). We also note that the determination of INOV amplitude and duty cycle in our UPSO program, for representative sets of RQQs (DC  $\sim 17\%$ ), LDQs ( $\sim 12\%$ ), CDQs ( $\sim 20\%$ ) and BL Lacs ( $\sim 72\%$ ), well matched in the  $z - M_B$  plane, was a first time endeavour, with the added advantage that the same instrumental set up and analysis procedure were used (and a typical INOV detection threshold of 1–2% achieved). Additional support to the above INOV characterization for the 4 most prominent classes of high luminosity AGN has come by harnessing an enlarged INOV database through new observations and quality data mining from the literature

(see below and Table 1). Here it is relevant to underline that, again somewhat unexpectedly, RQQs and CDQs show similar optical variability on week/month-like time scales (e.g., Bauer et al. 2009; Gaskell et al. 2006).

Early on, we pointed out that the photometric error given by the standard routine in IRAF is underestimated by a factor  $\eta \simeq 1.5$  and ignoring this in statistical tests can often lead to spurious variability claims (Gopal-Krishna et al. 1995). This correction factor has now become a standard part of the  $C$ -test and  $F$ -test (Goyal et al. 2013b and references therein).

### 3 Continuation of the INOV program in the ARIES era

Subsequent to the metamorphosis of UPSO into ARIES, our INOV program using the ST was pursued with an expanded scope by including other important classes of AGN whose INOV characteristics were largely unknown. These classes are: Radio-Intermediate Quasars (RIQs) and TeV blazars (Goyal et al. 2010; Gopal-Krishna et al. 2011). Secondly, the role of optical polarization in INOV was more thoroughly assessed using a sample of 16 CDQs (Goyal et al. 2012). Lastly, our vast database of about 250 intranight DLCs covering 6 major classes of AGN was uniformly re-analyzed by applying a more authentic statistical test, the  $F$ -test, newly emphasized by de Diego (2010). This yielded, for the first time, a uniform characterization of the INOV properties of 6 major classes of high-luminosity AGN, namely RQQs, RIQs, LDQs, LPCDQs, HPCDQs and TeV blazars (Goyal et al. 2013a; Table 1). The 1.04-m ST continued to be our workhorse even in this phase, although we did occasionally use the 2-m HCT of IIA and the 2-m Giravali telescope of IUCAA. The main results of this program are summarized below.

(a) *Radio-Intermediate-Quasars (RIQs)*: With a radio loudness parameter ( $R$ ) in the range  $\sim 3$  to 100, RIQs are a link between RQQs and RLQs. The possibility of their being counterparts of RQQs with Doppler boosted radio jets has been put forward (e.g., Miller et al. 1993; Falcke et al. 1996; Xu et al. 1999; Barvainis et al. 2005). Intranight R-band monitoring of 8 optically bright RIQs having flat or inverted radio spectra (hence jet dominated), was carried out on 25 nights during 2005–2009, yielding an estimate for INOV duty cycle, DC  $\sim 10\%$  and  $\psi \sim < 3\%$ . This shows that in INOV properties, RIQs are close cousins of CDQs, rather than blazar-like (Goyal et al. 2010).

(b) *What holds the key to INOV: Polarization or relativistic beaming?* This study was designed to probe the relationship of INOV with two key observational signatures of the blazar phenomenon, namely, optical polarization and radio core dominance. This point is relevant since, historically, a flat/inverted radio spectrum of a quasar, a marker of core dominance, has often been deemed adequate for a blazar classification (e.g., Wills et al. 1992; Maraschi & Tavecchio 2003). We performed 44 nights of intranight monitoring (typical duration  $\sim 5.7$  hour) of a sample consisting of 12 low polarization core-dominated quasars (LPCDQs,  $p < 2\%$ ) and 9 high polarization core-dominated quasars (HPCDQs,  $p > 4\%$ ). The two sets are otherwise matched in the  $z - M_B$  plane and radio spectral index (Goyal et al. 2012). Whereas, for the HPCDQs, a large INOV ( $\psi > 4\%$ ) occurred on 11 out of 22 nights, the same was seen for the LPCDQs on just 1 out of 22 nights. This striking contrast was the first unambiguous demonstration that the physical link of INOV with optical polarization is far more fundamental than that with the relativistic beaming of the nuclear jet, as manifested by a dominant radio core, or a flat/inverted radio spectrum. Significantly, this tight correlation holds even if the optical polarization had been measured in a distant past, implying that the propensity of a given FSRQ to exhibit (or, not exhibit) strong INOV is of a fairly stable nature (Goyal et al. 2012). These authors have also sketched a model for the correlation, in terms of a turbulent synchrotron plasma of the relativistically moving jet crossing standing shocks, just ahead of the jet's acceleration zone envisaged in the model by Marscher et al. (2008); also see Marscher (2014) and Pollack et al. (2016).

(c) *A search for INOV on sub-hour time scale (using TeV blazars)*: Under this first INOV campaign dedicated to TeV detected blazars, we monitored 9 TeV blazars on 26 nights for an average duration of 5.3 hours, and then combined those data with similar INOV data gathered from the literature for another 13 TeV blazars (90 nights). It was thus shown (Gopal-Krishna et al. 2011) that the well known trend for the low-peaked BL Lac objects (LBLs) to exhibit a distinctly stronger INOV, compared to high-peaked BL Lac objects (HBLs) (e.g., Heidt & Wagner 1998; Romero et al. 2002) persists even when their TeV detected subsets alone are considered. Secondly, despite a dense and extensive intranight sampling, the DLCs of the 22 TeV blazars did not

Table 1: INOV Duty Cycles using the  $F$ -test

AGN type	No. of sessions	INOV DC	INOV DC ( $\psi > 3\%$ )
Radio-quiet quasars (RQQs)	68	10%	6%
Radio-intermediate quasars (RIQs)	31	18%	11%
Lobe-dominated quasars (LDQs)	35	5%	3%
Low-polarization core dominated quasars (LPCDQs)	43	17%	10%
High-polarization core-dominated quasars (HPCDQs)	31	43%	38%
TeV detected blazars (TeVBLs)	85	45%	45%

reveal even a single credible feature on a time-scale substantially shorter than 1 hour (see, also, Sagar et al. 1999). This is particularly noteworthy since extremely large bulk Lorentz factors  $\Gamma > 50$  (and correspondingly stronger time compression) have been inferred from the brightness and rapid variability of TeV blazars, as their jets must be highly relativistic in order to avoid absorption of the TeV photons by co-spatial IR photons (e.g., Krawczynski et al. 2002; Aharonian et al. 2007; Begelman et al. 2008). Our search for sub-hour time scales was triggered by some claims (and counter-claims) in the literature on the issue of minute-scale optical variability of some blazars (e.g., as also noted in Romero et al. 2002). Here it is relevant to recall that even for EGRET blazars, the shortest time scale of INOV is seen to be  $\sim 1$  hour (Romero et al. 2000). Note also that a search for sub-hour time scales in the radio light curves of some prominent intra-day variable blazars has also proved negative (Krichbaum et al. 2002).

The shortest variability time-scale is important for understanding the geometry of jets and the magnetic field, because it provides a possible maximum size of the variable region. The very short timescales probe the conditions very close to the centre. Our negative search demonstrates that, unlike at X-ray and  $\gamma$ -ray bands, optical variability on minute-like timescales is really rare, at least for amplitudes above  $\sim 1\%$ . Nonetheless, a 15-min time scale has been detected in the optical light curve of the BL Lac object S5 0716+714 (Sasada et al. 2008; Rani et al. 2010; also, Wagner et al. 1996). The size of the optically emitting region corresponding to such time scales begins to match the Schwarzschild radius of the central black hole in high luminosity quasars.

(d) *Improved characterization of intranight optical variability of 6 prominent AGN classes (using the  $F$ -test)*: Until about 2010, the statistical test commonly used for checking the presence of INOV in DLCs was the so called,  $C$ -test, introduced by Jang & Miller (1997). However, de Diego (2010) questioned its validity on the ground that the  $C$ -statistic does not have a Gaussian description (as was commonly assumed). Instead, he advocated the use of  $F$ -test which compares the observed to expected variances (see, also Villforth et al. 2010). We therefore decided to re-evaluate the INOV characteristics of 6 major classes of powerful AGN, by applying the  $F$ -test to their existing  $\sim 300$  DLCs based on the intranight monitoring with the ST. The resulting estimates of the INOV DC are given in Table 1 which also lists the DC values for INOV amplitude  $\psi > 3\%$  (Goyal et al. 2013a). The motivation for this work was the need to establish a uniform benchmark for future INOV studies.

(e) *Multi-week, simultaneous multi-colour intranight monitoring of prominent BL Lac objects*: Multi-colour intranight monitoring of the prominent blazar S5 0716+714 was carried out in 1994 (21 nights) and 1996 (11 nights) using ST and VBT and of BL Lacertae in 2001 for 5 nights (Sagar et al. 1999; Stalin et al. 2006). While both blazars showed strong INOV in these observations they also revealed a contrasting INOV behaviour, on intranight and possibly also on internight scale. While BL Lac became bluer when brighter, no chromatic trend was seen for the variations of S5 0716+714. Once again, no sub-hour variations were detected even in these extensive INOV observations (37 nights) of two of the most active AGN.

(f) *Using INOV to search for the elusive radio-quiet BL Lacs*: Having consistently observed that an INOV amplitude  $\psi > 5\%$  flashes a BL Lac, we launched in 2012 a program of intranight monitoring of a carefully selected sample of the enigmatic and rare subclass of quasars, called ‘radio-quiet weak-line QSOs’ (RQWLQs). It has been speculated for many years that samples of RQWLQs might harbor some members of the long sought,

elusive minuscule population of *radio-quiet* BL Lacs, in analogy to quasars, most of which are in fact radio-quiet (e.g., Londish et al. 2002; Collinge et al. 2005; Stocke 2001; Shemmer et al. 2006). Since WLQs are mostly rather faint ( $m_V > 18 - 19$ m), this first-of-its-kind INOV project had to remain on hold until the installation of the 1.3-m telescope ('Devasthal Fast Optical Telescope': DFOT), our new workhorse.

Results from this ongoing program are presented in five papers (Gopal-Krishna et al. 2013; Chand et al. 2014; Kumar et al. 2015, 2016, 2017). These are based on intranight monitoring of 33 RQWLQs in 60 sessions lasting a minimum of 3 to 4 hours. Very briefly, two of the RQWLQs have exhibited episodes of strong INOV and another two have shown night-to-night variability, making them the best available candidates for the elusive radio-quiet BL Lacs. They are being further probed by optical polarimetric and continuum monitoring. Besides the Indian telescopes, the 2-m telescope in Haute-Provence (France) has also contributed to this project.

## 4 Major international collaborations

Photometry of the blazars Mrk 421 and 3C 454.3 taken in 2009–2010 at ARIES using the 1.04 m ST was studied along with X-ray data from *MAXI* and  $\gamma$ -ray measurements from *Fermi* (Gaur et al. 2012a). Both objects were in bright states then, and genuine INOV was detected for both objects. For Mrk 421 the X-ray fluctuations appeared to lead the optical ones by about 10 days. On the other hand, for 3C 454.3 the X-ray flux was not correlated with the optical (or  $\gamma$ ) fluxes, but the  $\gamma$ -ray changes apparently led the optical ones by around 4 days (Gaur et al. 2012a).

Ten low-energy peaked blazars were observed at ARIES and Mt. Abu between 2008–2009 for an average of four nights each and a duty cycle for their INOV was found to be about 52%; this is in accord with other measurements if the relatively short monitoring durations of  $\sim 4$  hours each are taken into account (Rani et al. 2011a). In 2009–2010 a substantial number, 17, of radio-quiet broad absorption line quasars (BALQSOs) were monitored at ARIES and another two were monitored with the Himalayan Chandra Telescope in Ladakh, for  $\sim 4$  hours each (Joshi et al. 2011). The majority of these BALQSOs did not exhibit clear INOV (only 2 of 19 did) though several others showed hints of changes. Hence radio-quiet BALQSOs seem to show roughly the same low duty cycle for INOV that is displayed by normal RQSOs (Joshi et al. 2011).

Over the past several years, Alok Gupta, his students, and others at ARIES have collaborated closely with a group of astronomers in Bulgaria to study INOV as well as longer term variability of many AGN, with a focus on blazars. This research has typically combined roughly equal amounts of photometric data taken with the 1.04 m ST and/or with the 1.3 m DFOT, with observations from several telescopes in Bulgaria, Greece, and occasionally Serbia. This set up can provide a longer continuous coverage of a given target on some nights, but more typically provides LCs on nights when only one of the observatories can successfully observe it.

Optical flux and color variations of 12 low-to-intermediate energy peaked blazars were studied for short-term (day-to-month) variations in 2008–2009 (Rani et al. 2010). Over those timescales, 92% showed significant flux variability and 33% showed clear color variations. The six BL Lac objects usually became bluer-when-brighter, while the six FSRQs displayed a weak opposite trend (Rani et al. 2010). The low energy (radio to optical) SEDs of 10 members of the above sample also were measured during 2008–2009 (Rani et al. 2011b), usually at multiple epochs. These could be well reproduced by a synchrotron model involving a log-parabolic distribution of electron energies and the variations in SEDs could be primarily attributed to changing jet Doppler factors (Rani et al. 2011b).

Multi-band optical observations of several blazars, including 3C 454.3, 3C 279 and S5 0716+714, all of which have been found to exhibit high INOV duty cycles, have frequently, but not consistently, shown bluer-when-brighter trends, particularly in overall active states (Agarwal et al. 2015; 2016). This type of chromatic change can be explained if the increasing synchrotron flux is related to a hardening of the underlying non-thermal electron spectrum and enhanced efficiency of particle acceleration. On the other hand, the high-energy peaked blazars 1ES 1959+650 and 1ES 2344+514 showed no genuine INOV over the course of observations covering 24 and 19 nights, respectively, in agreement with earlier studies suggesting that low-energy peaked blazars are more variable in optical bands (Gaur et al. 2012b and references therein).

BL Lac was in an active phase during 2010–2013 and ARIES observations were a key part of long term multi-band optical/NIR monitoring (Gaur et al. 2015a; see Fig. 1) that were combined with radio monitoring

conducted in Finland and Ukraine at several frequencies (Gaur et al. 2015b). During this period the cm-fluxes were delayed with respect to the optical by  $\sim 250$  days, but no typical variability timescales were found for either, implying an intrinsic origin for the radio variability. Additional multi-band monitoring of BL Lacertae was conducted on 13 nights in late 2014; it showed INOV on several of these nights and also displayed the bluer-when-brighter trend (Agarwal & Gupta 2015). Between 2012 and 2014, extensive observations of 3 TeV blazars, PKS 1510–089, PG 1553+113 and Mrk 501 were performed in the B, V, R and I bands at ARIES and in Bulgaria, Greece and Serbia. All three blazars remained active throughout the campaign, but no significant evidence was seen for spectral changes being correlated with the brightness of the source (Gupta et al. 2016).

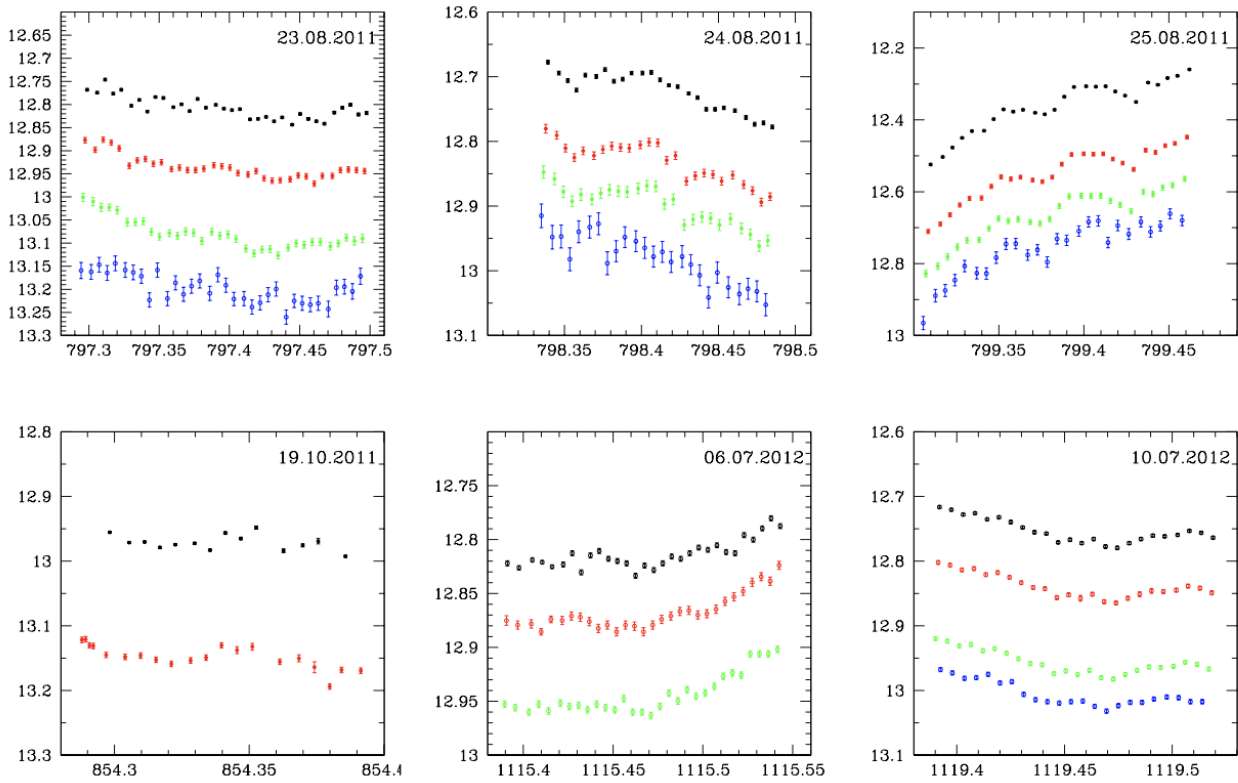


Figure 1: Multi-band intranight LCs of BL Lacertae in 2011 and 2012; B (blue), V (green), R (red) and I (black) bands, reproduced with permission from part of Figure 2 in Gaur et al. (2015a), MNRAS, 452, 4263. The X-axes are JD (2455000+) and the Y-axes are the magnitudes in each panel, with the B, V and I bands shifted by arbitrary offsets with respect to the best calibrated R-band LC.

Observations from ARIES have also contributed to several major “Whole Earth Blazar Telescope” (WEBT) campaigns that attempted to obtain essentially continuous LCs of particularly active objects for several consecutive days, by combining optical observations made with many ground based telescopes at different longitudes, so that the source always remains accessible to at least one telescope. In most cases, these WEBT campaigns are accompanied by simultaneous radio and X-ray, and sometimes with IR, UV and  $\gamma$ -ray, monitoring as well. Such coordinated multi-band observations of AGN yield instantaneous SEDs and their change with time. These measurements, particularly the temporal lags between fluctuations in different bands, provide critical information on the nature and location of the processes responsible for the acceleration of electrons to ultra-relativistic energies. WEBT campaigns to which ARIES contributed are those during 2007–2008 on 3C 454.3 (Raiteri et al. 2008), 3C 66A (Böttcher et al. 2009) and BL Lacertae (Raiteri et al. 2009), as well as one during February 2009 on S5 0716+714 (Bhatta et al. 2013).

ARIES led a similar multi-site, multi-band, campaign on S5 0716+714 for a week during December 2009 (Gupta et al. 2012): the key results were that large variations, with similar timescales, were seen in the radio and optical bands, but not in X-rays. Analyses of these data indicate that the radio fluctuations were dominated by

interstellar scintillations, the optical changes arose from intrinsic synchrotron emission, while the X-rays originated from inverse Compton scatterings. Together with nearly simultaneous  $\gamma$ -ray observations from *Fermi*, these data imply that the relativistic jet had a Doppler factor between 12 and 26, which is atypically large for a BL Lac (Gupta et al. 2012).

## 5 Epilogue

The phenomenon of AGN Intra-Night Optical Variability (INOV) earned wide acceptance and traction in the late 1980s, with the use of CCD cameras as multi-star photometers. However, this area of research was then pursued at just a couple of observatories in the USA and was basically confined to blazars, a tiny subset of Active Galactic Nuclei. In the early 1990s, its major diversification by the present authors to encompass several other prominent classes of powerful AGN, and its ensuing rapid growth and globalization has resulted in greatly enlarging the footprints of the INOV research, to at least a dozen countries spread across four continents. India's pioneering role in this diversification process has involved all major Indian optical observatories, leading to 101 refereed publications in international journals and receiving over 1900 citations. ARIES (formerly UPSO) has been at the forefront of this activity which is now poised for further expansion, taking advantage of its new telescopes at Devsthal, the 1.3-m DFOT and the just commissioned 3.6-m DOT.

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