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河外射电源变化的观测研究*

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摘 要

在本文中评述河外射电源变化的观测进展。首先对几个射电变源的一些专门术语和定义作介绍。然后叙述在整个频谱上（射电、红外、光学、紫外、X射线、γ射线）各种变化测量的结果，包括流量、频谱和偏振的变化。讨论了VLBI对变化研究的重要影响。简要地触及短时标变化引发的逆康普顿灾变的理论问题。最后，强调指出了多波段同时观测河外射电源在深入了解活动星系核方面的重要作用。

关键词 星系：核 — 类星体：一般 — 射电连续谱：星系 — 紫外：星系 —X射线：星系 —X射线：观测

Observational Study of Variability of Extragalactic Radio Sources

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Abstract

The observational progress in the study of the variability is reviewed. First, some concise nomenclature and definitions are introduced of several variable radio sources. Then, the results from various measurements of variability (such as variations of flux, spectra and polarization) over a wide frequency range(radio, infrared, optical, ultraviolet, X-ray and γ-ray) are presented. The impact of VLBI on the study of the variability is also discussed. As an introduction to the theoretical work, a short description of the inverse Compton catastrophe induced by short time-scale variation is given. Finally, the importance is emphasized of simultaneous multi-frequency campaigns, in the widening and deepening of our knowledge about active galactic nuclei.

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1 Introduction

The study of the variability of celestial objects has long been an important and active research field throughout the history of astronomy. It could provide us with much information about the activity in these objects, which is hard to be reached directly by other measurements. Such observations are essential for our understanding the physical conditions within sources and thus the radiation mechanism responsible for the properties observed. Furthermore, it will help us to discriminate among a variety of theoretical models and to understand how these sources evolve.

Nowadays, from the ground to the space, many large advanced astronomical instruments are in use to investigate such phenomenon. The wavelengths involved, ranging from low frequency radio wavelengths (~300 cm; ~100 MHz) to extremely energetic γ-rays ($\sim 10^{-15}$ cm; ~30 GeV), entirely cover an extraordinarily wide spectral regime. The targets of these observations include both galactic and extragalactic objects. In this review we will concentrate on the observations which have been made to study the variability of extragalactic radio sources, or more specifically, radio–loud AGNs (active galactic nuclei).

Generally, we could describe any radiation from a radio source with four Stokes parameters (i.e., I, Q, U and V), which are the functions of the frequency (ν), time (t) and two equatorial coordinates (α, δ). The functions Q and U (linear polarization) and V (circular polarization) carry important message about the magnetic field structure and particle densities in and around the source. But the measurements of them are rare due to the difficulty in observations of the intrinsically weak polarization for most sources. It is anticipated that such observations would be increased with the improvement of instruments. Most measurements to date are restricted to $I(\nu)$, $I(t)$ and $I(\alpha, \delta)$, which give the spectrum, time dependence of flux density and brightness distribution in the source, respectively.

In fact, almost all the astronomical phenomena are subject to variation of some sort. The time variations of flux density, polarization and structure are the themes of this review. It is believed, but poorly understood, that these different kinds of variation are related to the physical conditions and geometrical distributions in regions that are thought to be closely associated with the central energy source.

There are many technical terms used to name the different variables, mainly depending upon the properties discovered in the first observations. This partly reflects the different stages in the observational study of the variability. So, it is necessary, before we discuss the observational properties of the variability, to present a definition of these variables (see §2). The basic characteristics of variability of extragalactic radio sources at many observational aspects will be summarized in §3. The impact of VLBI on the study of the variability is discussed in §4. The theoretical explanations to these results are recapitulated in §5. Finally, the importance is emphasized in §6 of the simultaneous multi–frequency campaigns in probing the central engines of the sources and in distinguishing among models.

2 Definitions

According to the radio luminosity at 5 GHz ($L_{5\ \mathrm{GHz}} = 10^{24}\ \mathrm{W \cdot Hz^{-1} \cdot Sr^{-1}}$), AGNs could be divided into two classes: radio-quiet and radio-loud. The former class constitutes about 90% of AGNs, while the latter only about 10%. The so-called unified schemes try to explain the observational difference between two classes as the results of beaming effects and combine them under the same parent population.

Table 1 Summary of characteristics for different variables

Type	Radio Properties	Optical Properties
Blazars	compact size; high polarization; rapid variation	$P_{\mathrm{opt}} > 3\%$; weak line emission
BLOs	variability in flux density; high, variable polarization	no strong emission lines; high variation in flux and polarization
HPQs		$P_{\mathrm{opt}} > 3\%$; large, rapid flux variation
LFVs	large variation below 1 GHz	
OVVs	strong, varying polarization	> 1mag within days to weeks; variability in polarization

In this review we will focus the discussion on radio-loud objects. These bright sources can be further subdivided into many different types of variables. Because of the restrictions of the observation itself (such as the wavelength, sensitivity and resolution, etc) as well as some historical reasons, there is some confusion in the source nomenclature. It has been found that some distinctions of different classes of extragalactic radio variables have become common in a large class. This suggests that we search for an intrinsic mechanism behind them, and then unify these different classes physically. Such endeavors are continuing and much progress has been made.

In the following, we will try to present comprehensive definitions of several types of variables frequently mentioned in the study of the variability of extragalactic radio sources. Table 1 provides a brief summary of the observational properties at the radio and optical regimes of these different variables. It should be reminded that sometimes one-sentence definitions are inadequate to fully describe the properties of a specified class. Also, these definitions may vary among different researchers. It is in any case likely that some categories which have been used to classify objects reflect biases in the observational data, rather than some fundamental physical difference among the studied samples.

2.1 Superluminal radio sources

Superluminal radio sources are a class of radio sources, that have at least a subcomponent with apparent transverse velocity greater than the velocity of light[1]. Using the Friedmann-Robertson-Walker metric, we can derive the apparent transverse velocity $\beta_{\mathrm{app}}(=v_{\mathrm{app}}/c)$ from an observed internal proper motion μ

$$\beta_{\mathrm{app}}=\mu(q_0z+(q_0-1)(\sqrt{1+2q_0z}-1))/H_0q_0^2(1+z) \tag{1}$$

where H_0 and q_0 are the Hubble constant and deceleration parameter, z the redshift of the object identified with the radio source.

The discovery and confirmation of the superluminal sources have been acknowledged as a great contribution of VLBI to modern astrophysics. A much more detailed description can be found in Superluminal Radio Sources[2] and the references therein. Since the first superluminal source (3C279[3]) was discovered, there have been more than 30 additional such sources confirmed by (at least) two-epoch VLBI observations. From the view of the variability, superluminal motion is a kind of temporal variation of source structure and its flux density as well. The combination of the high dynamic range VLBI imaging observations with high resolution and flux density monitoring will be extremely helpful in the task of connecting the change of source structure with that of flux density.

2.2 Optically violent variables (OVVs)

Since they were first identified, OVVs, as a class of objects in the study of the variability, have been studied intensively (e.g. in [4]). The first sample of OVVs was given by Penston and Cannon[5]. They designated the term OVVs to those sources exhibiting changes of optical brightness larger than one magnitude within days to weeks. Such rapid optical change imposes a severe restriction on the upper limit of the optical emission region size. The polarization observations at multi−frequency[6] show that, OVVs have strong and variable polarizations at radio as well as at the optical wavelength. Most OVVs usually are compact radio sources, and the superluminal motions have been detected in some OVVs. The spectra of OVVs are flat in the radio regime, and become steep in the optical and infrared regimes.

2.3 BL Lac objects (BLOs) or BL lacertids

The definition of BLOs is derived from the study of BL Lacertae, which is the prototype of the class. Schmitt's identification[7] of BL Lacertae with the unusual radio source VRO 42.22.01[8] began an active study of this peculiar object. Subsequent observations showed that it had rapid variations in its radio flux density and linear polarization. The optical radiation exhibited a continuous spectrum with neither emission nor absorption lines, but a relatively high degree of linear polarization.

When four other objects (OJ 287, ON 231, ON 235 and OR 225) were found to have similar features to those of BL Lac in 1972, there were indications of the existence of this new class with the following characteristics[9]: (1) rapid variations in radio, infrared, and optical fluxes; (2) absence of discrete features in optical spectra; (3) high and rapidly varying polarizations at optical and radio wavelengths; and (4) most of the radiant energy is emitted at infrared wavelength. It appeared from the early observations that BLOs are extremely compact non-thermal objects, and they are very similar to the quasi-stellar objects (QSOs) except that they have no spectral lines.

However, observers soon detected weak emission lines in some sources of this class (e.g., 3C371[10]). Miller and Hawley[11] also discovered the stellar absorption lines and faint emission lines in BL Lac itself. It is generally recognized that some BLOs have no feature in their optical spectra while others have very weak emission lines. As high quality spectral information is obtained on more sources, it appears that the detection of line emission is, at least to some extent, a problem of contrast with the strength of the continuum. This presents a constraint on the non-thermal radiation of BLOs. If BLOs belong to the inherently more luminous FRII (Fanaroff-Riley type II[12], whose radio luminosity at 178 MHz is above $10^{25}\mathrm{W}\cdot\mathrm{Hz}^{-1}\cdot\mathrm{Sr}^{-1}$ with radio emission brightest at the edge of the radio lobe) radio galaxies or quasars, the strength of radiation should be much stronger. Otherwise, unifying the intrinsically weak FRI (Fanaroff-Riley type I[12], whose radio luminosity at 178 MHz is below $10^{25}\mathrm{W}\cdot\mathrm{Hz}^{-1}\cdot\mathrm{Sr}^{-1}$ with radio brightness peaked around the optical counterpart) radio galaxies with BLOs needs moderate radiation in BLOs. More detailed study of BLOs can be found in the Proceedings of the Pittsburgh Conference on BL Lac Objects[13] and in BL Lac Objects[14]. The number of identified BLOs is about 90.

2.4 Low frequency variables (LFVs)

In brief, LFVs are those radio sources which display temporal flux variations at frequencies below 1 GHz[15]. The class of LFVs being introduced into radio astronomy can be traced to the pioneering observations by Hunstead[16] at 408 MHz. The time-scale of LFVs appears to range from few months to a year with the fractional changes as large as 50%. This imposed a significant challenge to explaining these sources in terms of intrinsic variability. However, it is now widely believed that most of LFVs are caused by RISS (refractive interstellar scintillation)[17–18]. Therefore, these temporal variations are extrinsic. This could be also inferred from the results of Cawthorne and Rickett[19] and Gregorini, Ficarra and Padrielli[20], that the percentage of LFVs is significantly higher at low galactic latitude. Only few LFVs show the intrinsic variability that is related to source structural variations such as those seen in the superluminal radio sources.

2.5 Highly polarized quasars (HPQs)

Moore and Stockman[21] identified a class of quasars having a high degree of optical polarization ($P_{\rm opt} > 3\%$) and called them highly polarized quasars (HPQs). The observations showed that HPQs have large and rapid optical flux variations, steep spectra in the optical-infrared band and very strong radio emission with flat spectra. HPQs are similar to BLOs. HPQs may be intermediate objects between low polarization (normal) QSOs and BLOs. Statistical analysis showed that there is a significant correlation between the large optical outburst and the high, variable, optical linear polarization, and almost all HPQs are OVVs too.

2.6 Blazars

In 1978, the first conference on BL Lac Objects was held at the University of Pittsburgh. The term "Blazar" was coined by Ed Spiegel to encompass all the variables discussed in that meeting, most of which were BLOs.

Since then, there have been many definitions on blazars. Angel and Stockman[22] defined blazars as AGNs with optical polarizations large than 2%—3%. Bregman[23] thought that non-thermal radiation in the radio through ultraviolet regime could be inferred from the high brightness temperatures because of the rapid variability of blazars. Impey[24] characterized the blazars with following four properties: (1) compact radio sources; (2) high polarization; (3) rapid variability; and (4) weak emission lines. Since BLOs, OVVs and HPQs all exhibit very similar properties in the variability, we will discuss BLOs, OVVs and HPQs as a single entity under the name of blazars, if there is no any special indication in the text. There are $\sim$ 200 blazars confirmed from observations.

3 Observational Properties of Variable Radio Sources

In general, variability observations of radio sources include the measurement of fluctuations of flux density, spectrum and polarization. In this section, we will summarize these observations and their results.

3.1 Variations of radio flux densities

From 1964 to 1965, Sholomitskii[25] observed some radio sources at the frequency of 923 MHz (λ 32.5 cm). During about 100d period, the flux density ratio of CTA 102 and 3C 84 exhibited an as large as 30% variation, while the ratio of CTA 21 and 3C 84 remained constant within 5%. At the same time, Dent[26] reported that 3C 273 had a 40% increase in the flux density at 3.75 cm over a 1000d period. The implications of their discoveries were clearly very important, although some confirming observations were still needed then. An excellent review of early history can be found in [27].

Generally speaking, the measured radio flux densities at different epochs could not be equal. This does not mean that all the AGNs are blazars. In fact, the number of known blazars is very small (~200) compared to the number of quasars (~7000[28]). Identification of time variability of a source requires a careful calibration and a long term commitment. Such work is widely carried out around the world. In the following, we will introduce the work of several well-known projects, which help us to investigate the range of the variability phenomena by providing us with a homogeneous set of high-quality data for testing theoretical models of the objects.

The University of Michigan group has conducted a monitoring program with 26-m paraboloid in both total and linearly polarized flux since 1965 ([26]; [29] and references therein; [30]). They discovered the first evidence of the polarization variability at 8.0 GHz[31]. At 8.0 GHz, the observations were started in 1965, at 14.5 GHz in 1974, and at 4.8 GHz in 1978. This data base provides many high-quality, high time resolution (better than 1 month) multi-frequency radio light curves spanning more than one decade. Most of the target sources are BLOs and OVVs. Seen from the light curves, BLOs have much more rapid (shorter time-scales) and much stronger (larger fractional amplitudes) variations than others.

Nicolson *et al.*[32] from South Africa have observed southern blazars for a long time. The wavelengths used are 13.6 and 3.6 cm. Having analysed the data of past 20 years, they found that about 87% sources with flat spectra had flux density variations at 13.6 cm, but only 45% showed drastic outburst properties of blazars. They concluded that the radio measurements are insufficient to distinguish among different classes of blazars (such as BLOs, HPQs and OVVs).

Since 1980, Valtaoja and his collaborators have done much work on high frequency monitoring[33–39]. They carried out a large sample monitoring of extragalactic radio sources, at 12, 22, 37, 77 and 87 GHz, using the 13.7m radio telescope at Metsähovi Radio Research Station and sometimes the 22m telescope at the Crimean Astrophysical Observatory. They found that the duration of radio outbursts ranged from a few months to 2 years. They also reached the same conclusion as Nicolson *et al.*, that it is impossible at high frequency to discriminate among different kinds of blazars. They also carried out a series of continuum observations of blazars[40], including (1) surveying of 34 BLOs and 29 HPQs in the southern hemisphere and (2) monitoring of highly active blazars, by means of the 15m SEST (Swedish–ESO submillimeter telescope) at the frequencies of 100 and 230 GHz. With the statistical analysis of about 50 southern blazars, they concluded that at high frequencies the variations of HPQs are stronger than those of BLOs, and that the time-scale of variability is about 200 days. They noticed that the averaged fractional amplitude over a long time is not so large, and explained this as the results of the stability of central core component.

Another even higher frequency monitoring program is going on now. This is the sub-millimeter observations made by Steppe *et al.*[41–42] with the 30m telescope at Pico

Veleta near Granada, Spain, and later the 15m telescope on Plateau de Bure, France. The observations provide data for the variability studies at frequencies of 90, 110, 150 and 230 GHz, where most BLOs are found particularly active. The significant variability at 3 mm has been noticed and its correlation with 1.3 mm variability (if data available) is also confirmed. Such observations have particular importance as they could be used to connect the results from other wavelengths (such as infrared, optical and X-ray) and therefore help to discern the innermost physical process of blazars.

The time-scale of variations of extragalactic radio sources ranges from a few weeks to a few years, with most common value being about a few months. This indicates that the size of radio radiation region on average should be larger than a light-week ($\sim 10^{16}$ cm). Therefore, any flux changes with much shorter time-scale may not be physically related to source itself.

Variability on even shorter time-scale (hours to days) with much larger amplitude change ($>$ 10%—20%) is called intraday variability. Prior to 1985, few observations were available on intraday variability (e.g., [43] and appendix therein). Kikuchi *et al.*[44] observed a 20% decrease in the 7.2 cm flux density of OJ 287 over 100 minutes. Epstein, Landau and Rather[43] observed 33 extragalactic variables at 90 GHz in a search for daily and hourly variations. They found that OV−236 (1921−293) had a drop in its flux density by a factor of 2.7 (from 6.4 Jy to 2.4 Jy) over a three-day interval, and rose to its previous value two days later. After they examined many possible explanations, they concluded that this large drop within so short time-scale was intrinsic to the source.

Heeschen *et al.*[45] first noticed that even at 11 cm, some sources (e.g., 0716+71, 0917+624, etc.) showed amplitude changes larger than 10% within few hours to few days. For example, the variation of total flux density of 0917+624 in a day is about 25%. Subsequent detailed observations at 6 and 11 cm confirmed this[46−47]. The origin of such intraday variability is not clear at present, but there are many plausible explanations. Any intrinsic models would encounter the problem of Compton catastrophe, which is difficult to avoid because of small size inferred from intraday changes. The explanations using the refraction and reflection by interstellar medium require smaller and denser interstellar scintillation matter. These extrinsic models cannot explain the observed large changes in polarized flux density (e.g., the polarized flux density in 0917+624 varied by a factor of three[48].).

Astronomers[48−49] in a group of MPIfR suggest that the observed intraday variability include two parts: (1) small amplitude variation caused by RISS and (2) large amplitude variation induced by an intrinsic mechanism, which is correlated with the observed variability at optical wavelength. The solution to this problem depends upon the simultaneous multi-frequency monitoring.

3.2 Variations of spectral flux densities

The observations of the activity of blazars show that outbursts generally appear first at shorter and then at longer wavelengths. It has become clear in recent years that the best way to discriminate among various models of the continuum emission in blazars is to measure the spectral shape over as wide a range in frequency as possible, and even more importantly, at intervals as close as possible.

Landau *et al.*[50] analyzed spectra, observed simultaneously over six decades in frequency (radio to ultraviolet) of source rest frame, of 25 active sources, and found that their spectra could be nicely modelled with a three-parameter parabola

$$\log S_\nu = C + (\log\nu - B)^2/2A \tag{2}$$

These parameters (A, B, and C) are correlated each other. This differs from the spectral energy distribution ($\log\nu S_\nu$ vs $\log\nu$) of the ordinary AGNs(see Fig. 8 in Lawrence[51]), which has some distinct features at several different frequency regimes. Landau *et al.* argued that the striking similarity among so many observed spectra and so wide a frequency range suggests that parameters of source models could not be chosen freely from source to source, i.e., either some are universally fixed or there are physical relationships among them, although they have not been identified.

In order to obtain a wide spectrum of a blazar, many careful measurements of spectral flux densities in different electromagnetic wavebands are needed. So, the study of the spectral variability mainly depends upon the observations at various frequencies. There have been many such measurements covering almost entire frequency range available for astronomical observations. We will briefly list some of these observations, with emphasis on the most recent ones.

- **Radio**

  There are many well-known VLA and VLBI observations, in addition to abovementioned single-dish monitoring programme (3.1). For example, 54 blazars known at the time of the Angel and Stockman[22] review paper, were mapped by VLA at 20 cm[52–54]. Pearson and Readhead[55–56] conducted a VLBI survey of a large sample of 65 extragalactic radio sources. Wehrle *et al.*[57] made extensive VLBI observations of some 41 strong variables.

- **Infrared**

  Observations in this region are essential for determining the properties of the most compact regions where the transition from optically thick to optically thin emission occurs. The typical time-scale is about a few months[58]. The researches from several groups[59–62] showed that blazars tend to be more variable than normal AGNs and they are dominated by the non-thermal emission.

- **Optical**

The variability of objects was first observed in visual wavelength. OVVs were discovered and named on the basis of optical measurements[5]. Observers have accumulated photometric data for many large samples in the optical regime since the beginning of OVVs study[63]. Special attention is now being paid to the study of some individual sources[64−69], by means of the optical photometry and spectroscopy. The time-scale of optical variations ranges from years to less than a day.

- **Ultraviolet**

Blazars usually show stronger variability in the ultraviolet than in the optical wavelengths. Analysis of variability in this region is based on the observations with IUE (International Ultraviolet Explorer)[70]. About 55% of blazars varied by over a factor of 2 in IUE observations[71]. PKS 2155–304 was found to have a power-law ($S_\nu \propto \nu^{-\alpha}$) spectrum at ultraviolet region, with an average spectral index of 0.89[72]. This index has changed very little although the ultraviolet flux density has varied by a factor of ~2. The time-scale is as short as 10 days in PKS 2155–304. There is a clear evidence of a more rapid change with time-scale of 5 hours in this source[73].

- **X-ray**

The shortest time-scale in the variability of blazars was observed in X-ray bands. For example, Felgelson *et al.*[74] discovered a 30second variation in a newly discovered BLO (H0323+022) in the data of the first High Energy Astronomy Observatory (HEAO-1) all-sky survey. The X-ray measurements are generally from the archives of many satellites, such as HEAO-1, EXOSAT, EINSTEIN, GINGA and ROSAT, etc. The average spectral indices of BLOs are steeper than those of HPQs and ordinary flat-spectral QSOs in the X-ray bands. There are some systematic differences between X-ray selected and otherwise selected objects. The strong X-ray sources may be weak at radio wavelengths. Therefore, we must study X-ray selected blazars and radio-selected blazars, separately. Maraschi *et al.*[75] studied a sample of 75 blazars, 13 of which is X-ray selected. They confirmed that X-ray selected objects have on average significantly flatter spectral indices than radio-selected blazars. Also X-ray selected blazars are underluminous at ultraviolet and radio frequencies. Schwartz *et al.* identified 20 X-ray sources in HEAO-1 catalog with bright and hard X-ray emitting BLOs[76]. In the European X-ray Observatory Satellite (EXOSAT) data of some BLOs, the X-ray flux and spectral index appeared to be correlated, in the sense that X-ray spectrum hardens as the source brightens[77−78]. The Giommi group[79] made a systematic analysis of 36 BLOs data from EXOSAT data, and found that these BLOs have strong luminosity variability (in the case of PKS 2005−489, it reached a factor of 30). Such variability was more prominent in the hard (0.7–8keV) X-ray bands than in soft (0.05–2keV) X-rays. The Maccacaro group[80] extracted a sample of 32 X-ray selected BLOs from the EINSTEIN survey. They argued that the X-ray survey provided an efficient means for searching for new BLOs[81]. Ohashi[82] reported the study of BLOs variability with GINGA. Sambruna *et al.*[83] presented a preliminary result of spectral analysis of ROSAT observations for a complete sample of radio-selected BLOs from Stickel *et al.* sample[84].

- **γ-ray**

  To date most of what we know about blazars at γ-ray is from the observations of Compton Gamma Ray Observatory (CGRO)[85−87]. For instance, 3C279, the most luminous γ-ray source yet detected, was detected throughout the energy range from 30MeV to over 5GeV by the EGRET (energetic gamma-ray experiment telescope) instrument on CGRO, although it was not detected by either of the earlier high-energy γ-ray telescope SAS2 or COSB. The observations of the time variability in the γ-ray emission of 3C279 are consistent with the model in which γ-rays result from the Compton scattering of low-energy photons by relativistic electrons in a jet. It is noted that virtually all of the AGNs, detected so far at γ-ray energies by the EGRET on CGRO, are blazars.

After many measurements at different wavelengths are made for a specific source, we can obtain a wide spectral energy distribution. But, there are still some problems with such wide spectra. The measurements at different frequencies were usually taken at different epochs. So, we should keep in mind that the wide spectra sometimes cannot represent the physical process in sources at a certain time, especially in the study of blazars, as one of the most prominent characteristics of blazars is rapid temporal variation of flux density, either outburst or decay.

3.3 Variations of polarization

Polarization measurements provide a powerful diagnostic tool for the understanding of the physical condition in either the emission region, where the polarization is connected with the emission mechanism, or the region where the incident radiation becomes polarized. High and variable polarization is one of the defining characteristics of blazars. HPQs are almost always associated with large amplitude optical variations, in contrast to most quasars which are unpolarized and quiescent. Therefore, linear polarization measurements may be a primary confirming attribute of blazars. For example, Impey and Tapia[88] discovered 31 blazars from optical polarimetry data. Several large monitoring programs[89−93] on blazars polarization have been conducted at the optical and infrared wavelengths. These measurements found that the linear polarization varies on time-scales from days to weeks to years.

The most important polarization properties of blazars are the so-called FDP (frequency-dependent polarization) and FDPA (frequency-dependent position angle), i.e., large changes in both the degree of linear polarization (p) and the polarization angle (Θ) through different spectral regions. For example, Puschell and Stein[94] obtained evidence for an increase in p with decreasing wavelengths from 1.65 μm to 0.36 μm in BL Lac, and change in the Θ ($\sim 10^0$) with wavelengths from 2.28 μm to 0.55 μm for 0754+101. Takalo *et al.*[95] first detected the daily variation of FDP and FDPA in OJ287. FDP and FDPA were found and confirmed only when the observations have been simultaneous in several wavelengths[96], as the occurrence of spectral change in the polarization is much rarer than temporal one. There seems to be no correlation between FDP and FDPA. The observations[97] of 0917+624 showed an anti-correlation between the variations in total flux density and the degree of polarization, that is, when the flux density increases, the polarization degree decreases, and vice versa.

Wavelength-dependent polarization in blazars is still a little understood phenomenon. As the frequency coverage of the polarization measurements in blazars has increased, there is mounting evidence that, at least in some objects, FDP is intrinsic to the source and thus due to the combination of the emission process and source geometry. Because of the energy loss or cutoff, the linear polarization of synchrotron emission may become slightly wavelength dependent. So, it was once proposed that the polarization is produced by synchrotron radiation. But the predicted rise of the polarization with frequency is too small an effect to account for the observed FDP, and some other mechanism must be sought. The so-called two-component model, consisting of two synchrotron components with different spectral indices, is widely used to explain the observed FDP and FDPA in individual blazars[89].

4 The Impact of VLBI on the Study of Variability

It is important to study the source structural variation as well as the temporal variability of flux density and polarization. It is the technique of VLBI that provides unprecedented angular resolution for observations of source structure. VLBI was introduced into radio astronomy[98,99], soon after the discovery of rapid variations in the radio flux densities. Later, the data analysis of VLBI observations showed that variations in flux density were accompanied by variations of structure (i.e., the changes in the correlated flux density over some baselines). More detailed observations resulted in the discovery of faster-than-light expansion in the 3C279. About half of the confirmed superluminal sources are blazars (5 OVVs and 10 BLOs).

In this section we concentrate on the relationship between the small-scale structure and variability of blazars, with a brief description of source morphology and classification from VLBI observations. More detailed discussions can be found in the Proceedings of IAU Symposium 110[100], IAU Symposium 129[101], and in the Proceedings of the Workshop on Superluminal Radio Sources [2], Proceedings of Symposium on Sub-Arcsecond Radio Astronomy[102] and Proceedings of the Workshop on Compact Extragalactic Radio Sources [103].

The most famous classification of small-scale structures with VLBI observations comes from the Pearson-Readhead survey[56] at 5.0GHz. Their observations showed a variety of morphologies among radio sources. Three major categories, which have been widely accepted, are: (i) very compact sources (unresolved or barely resolved with the highest resolution VLBI observations); (ii) asymmetric sources (an unresolved flat-spectrum core with high T_b and a diffuse steep-spectrum linear structure to one side, i.e. core-jet); and (iii) symmetric sources or "compact doubles" (two components of almost equal T_b and spectra). Wehrle *et al.*[57] observed a sample of 41 variable sources at 8 GHz. They obtained a similar distribution of morphologies. The first Caltech-Jodrell Bank VLBI survey (CJ1) carried out by Pearson *et al.*[104] extends the work of Pearson and Readhead. They observed a total of 135 sources in snapshot mode and discovered a class of "compact symmetric objects"(CSO)[105]. Thus far the confirmed CSOs are all galaxies, and have low radio polarization and variability. Also, Conway *et al.*[106] define a new class: compact triple, which consists of three principal components that lie almost on a straight line.

The variability in blazars is associated with their compact structures. The very compact sources in the Pearson-Readhead classification are highly variable[107], and the variability is correlated with VLBI structural compactness. This probably reflect the fact that such variability is intrinsic. The large total flux density variability at high frequency obviously should be related to the activity of the compact cores. Combined with the strong correlations found between total radio flux density and X-ray flux, the coincidence suggests that the X-ray may be generated near the radio emission region. But not all the blazars have only a compact core. Generally, most blazars have a parsec-scale jet, and can be classified as core-jet sources. Shocks propagating along the jet may be responsible for much of the flux variability. In some objects of core-jet morphology, a radio flux density outburst coincides with the appearance of an emerging of a new component, whose flux density decreases as it separates. From the VLBI morphology, it is generally argued that BLOs are strongly core-dominated and have slightly curved jets, while OVVs are lobe-dominated and have better aligned jets[108]. Observers are trying to collect such evidence to probe the physical mechanism responsible for the behaviour of variable flux density and structure.

At present, the monitoring of source structure is limited for blazars, as opposed to the monitoring of total flux density, although such systematic surveys for compact sources are being carried out all over the world. Therefore it is difficult to obtain a clear picture relating the flux outburst to structural change now. However, it is believed that future VLBI observations of blazars, will provide us more insight on the variability and its evolution. Especially, with the high dynamic range and resolution of VLBI imaging (such as VLBA), we could decompose the radio spectra of blazars. To date only a small number of blazars, e.g., 3C 345[109], have been examined at this level. This will help us to identify the emission from different components and could shed much light on the nature of these sources.

5 Theoretical Explanation

There are many models to explain the behavior of blazars. A fundamental boundary condition for these models has been to resolve the so-called inverse Compton catastrophe implied from the short variability time-scale. The brightness temperture T_b can be expressed as

$$T_b(10^{12}\mathrm{K}) = 1.22\,[S/\mathrm{Jy}]\,[\nu/\mathrm{GHz}]^{-2}\,[\theta/\mathrm{mas}]^{-2}\,(1+z) \tag{3}$$

where we assume a Gaussian brightness distribution whose angular diameter θ is either measured directly from VLBI, or obtained from the observed variability time-scale $t_v = S/[\mathrm{d}S/\mathrm{d}t]$ approximately

$$t_v \le t_{\max} = S_{\max}/[\Delta S/\Delta t] \tag{4}$$

where ΔS is the fluctuation of flux density in Δt, $S_{\max}$ is the maximum flux density observed, and $t_{\max}$ denotes maximum possible time-scale. So we can get the maximum angular size

$$\theta_{\max}(\mathrm{mas}) = 0.13[t_{\max}/\mathrm{yr}](1+z)/[D_L/\mathrm{Gpc}] \tag{5}$$

where D_L is the luminosity distance, which can be calculated, given the cosmological model. Brightness tempertures derived from variability time-scales are often several orders of magnitude higher than the theoretical limit of 10^{12} K, in which case the source is expected to lose its energy very rapidly. This is the so-called inverse Compton catastrophe. One of the more successful models was proposed originally by Rees[110]. It invoked relativistical effects. Since then, many advanced models have been proposed and modified. There are many excellent reviews (e.g., [18]) and we do not intend to give any further discussion on this issue.

Inevitably in a brief review such as this it is impossible to do full justice to such a large area of research. However, it seems clear that there is no comprehensive model to explain all the observed properties. Many models are successful in explaining some features of the observed variations in some sources. There are unified schemes, which are accurate to zeroth order and represent major progress in our understanding of AGNs. For a more description of such a theory, see the recent review given by Antonucci[111] and the references therein.

Many astrophysicists have expressed frustration that the theoretical study of AGNs is extremely imprecise compared to the study of stellar structure. In the analogy of Lawrence[51], our study of outward appearance of AGNs is like trying to understand the Sun from the Earth's weather. We have just a roughly correct classification in 1990s. The satisfactory fundamental theory will not be completed for a long time.

We end this section with a household parable: the blind men and the elephant, each man focusing on the distinguishing features of the elephant's anatomy he happens to be touching. Now it is the time that we combine all the information to devise, confine and modify models.

6 Progress and Prospect

When retracing the history of the variability study, we could see the following themes: first, several strong active objects were detected at some specific frequencies (such as OVVs discovered in optical) (see 2); then, such variability was also found at other frequencies (see 3.2); furthermore, (quasi-)simultaneous two or three band observations were carried out, and correlation analysis between a widely separated regions of the electromagnetic spectrum became possible; now, people began to undertake a series of simultaneous observations over 10 more decades in frequencies from radio to X-ray. Some day we will observe blazars simultaneously over an even wider frequency band extending to γ-ray.

Study of the variability of blazars has contributed much in extending our knowledge about AGNs. The observed rapid variation at radio frequency leads us to the postulation of highly relativistic beaming model, which has been widely accepted in explaining many observed features such as the superluminal motion, one-sided core-jet morphology, and observed weaker X-ray flux density, etc. This also could be used to solve the inverse Compton catastrophe. However, there are many alternatives to this relativistic jet model. For instance, Ostriker and Vietri argued that some BLOs are artifacts of gravitational lensing[112,113]. They proposed that most of BLOs are OVVs and some BLOs are actually distant OVVs lensed by intervening galaxies. To resolve many of these issues and allow strong constraints and tests of models, multi-wavelength observations are extremely needed. Because of the variability of brightness in blazars, only with the prevalence of the simultaneous multi-wavelength observations, can we study these phenomena more accurately than ever before.

Due to the instrumental and observational limitations, observations of blazars fall into one of three separate frequency regimes: radio ($\leq 10^{12}$ Hz), infrared-ultraviolet ($10^{13.5}$ – $10^{15.5}$ Hz), and X-ray (10^{17} – 10^{18} Hz). The multifrequency observations of the variability of blazars, especially simultaneously, are still rather scarce. Bregman and his collaborators began a program of simultaneous multifrequency (including radio, infrared, optical, ultraviolet and X-ray) observations of BLOs and OVVs. They have obtained several sets of simultaneous wide spectra for about five sources[114–118]. Some other groups have also made simultaneous or quasi-simultaneous observations for a dozen of sources[119–129]. These observations support the idea that the infrared to ultraviolet flux density emanates from a small region, while X-rays are produced by the inverse Compton process in the radio-emitting region. They further suggest that radio and X-ray emitting region is larger than that of infrared-ultraviolet.

The observations of carefully defined complete samples would be even more useful for statistical work. Having analysed the multifrequency, quasi-simultaneous spectra for a sample of 11 blazars, Brown *et al.*[130] found that the shapes of a lot of blazars spectra indicated the presence of at least two synchrotron components, one dominating the submillimeter to ultraviolet blazars flux and becoming self-absorbed in submillimeter/millimeter wavelength region, and another dominating the centimeter emission and becoming self-absorbed at ~ 2–5cm. Stickel *et al.*[84] provided the first homogeneous, flux limited sample of 34 BLOs taken from the 1Jy survey of Kühr *et al*[131]. Sambruna *et al.*[83] are working on data reduction of ROSAT survey for this sample. No systematic multifrequency observations of this sample has ever been carried out simultaneously, although Padovani[132] has made a statistical analysis using the published data at radio (5GHz), optical (5000Å) and X-ray (1keV).

Many observations of blazars are still suffering from insufficient sampling, frequency coverage, angular resolution and lack of polarization measurements, which limit the usefulness of these data. Multifrequency observations could expand the frequency coverage. An extremely high resolution could be obtained by means of VLBI, especially space VLBI projects (e.g. VSOP and RadioAstron). The observations of polarization, both in flux density measurement and mapping, are in progress steadily (see [133] and [134]). Although no real breakthroughs have been achieved as yet, there is no doubt that future progress towards understanding the complex phenomena in blazars will come about through such campaigns to obtain simultaneous multifrequency (from radio to X-ray and even γ-ray) measurements with as high resolution as possible.

To end this review, we would like to quote the following words to reiterate the importance of observations. This is from a report on a September 1993 conference called "Active Galactic Nuclei Across the Electromagnetic Spectrum" given by Shields and

Peterson[87]: (Maybe) "many of the 'right' ideas were already around more than 25 years ago. However, there were so few observational constraints on the theories that the few 'right' ideas were nearly impossible to distinguish from the many 'wrong' ones.".

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