ASTRONOMICAL PLATE ARCHIVES AND SUPERMASSIVE BLACK HOLE BINARIES

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Abstract. The recent extensive digitisation of astronomical photographic plate archives, the development of new dedicated software and the use of powerful computers have for the first time enabled effective data mining in extensive plate databases, with wide applications in various fields of recent astrophysics. As an example, analyses of supermassive binary black holes (binary blazars) require very long time intervals (50 years and more), which cannot be provided by other data sources. Examples of data obtained from data mining in plate archives are presented and briefly discussed.

Keywords: astronomical data archives, astronomical plates, photographic photometry, blazars, binary blazars, supermassive black hole binaries.

1. Introduction

The multispectral approach has proved to be an important tool in understanding physical processes in virtually all categories of astrophysical sources. A large fraction of high-energy celestial sources exhibit optical emission, and can hence also be observed and investigated in optical light. These investigations are far less expensive than satellite measurements, but can also provide valuable data.

Optical monitoring can be performed using modern devices, e.g. robotic telescopes. However, the real use of robotic monitoring telescopes remains somewhat limited, and even these automated devices are usually unable to achieve time coverage of the order of ten years and more, and are definitely unable to go back in time. However, long-term monitoring of many celestial high-energy sources, such as AGNs/blazars, may be crucial for understanding them, since they often show long-term evolution, various activity states, brightness variations and/or flaring. Data recorded in astronomical photographic plate archives can provide crucial data.

Combined data from several (or many) large plate collections can yield as much as some tens of thousands of monitoring hours for a particular sky position – one full life of an astronomer would be required to obtain the same observing coverage every clear night using a CCD telescope. In the past, data mining in astronomical plate archives was laborious and time-consuming, as it was based on human evaluation. However, recent widespread digitisation of the plates, as well as the availability of powerful computers and novel special software, now for the first time allow effective data extraction and evaluation.

In general, covering very large time intervals is a difficult but important task in astronomy and astrophysics. Archival photographic plates are a valuable tool in high-energy astrophysics, especially because they provide extensive monitoring intervals with good sampling, allowing long-term evolution and changes to be studied, as well as detecting flares and other variations in brightness. Photographic sky monitoring has been available for more than 100 years. Recent estimates indicate that there are at least 5 million (i.e. more than originally anticipated) astronomical archival plates worldwide, located in various observatories [1]. These archives can easily provide thousands of exposures for any celestial position, reaching monitoring intervals of up to a few years of continuous monitoring – i.e. tens of thousands of hours. Some of the archives have very high quality plates achieving limiting magnitudes of up to 20–23 (direct imaging) and/or 17–19 (spectral with objective prism). Recent efforts to digitise the plates and the corresponding software development have significantly facilitated the extraction of unique scientific data from archival records and related reductions and analysis. Some of the archives already have devices for digitising plates, and a few of them have already started extensive digitisation of the plates (e.g. Sonneberg Observatory – about 260 000 plates already scanned, Figs. 1 and 2). There are plans to use this data for an automated scientific evaluation of the objects on the plates and for creating their light curves.

2. Astronomical plate archives and HE/UHE astrophysics: motivation

As was mentioned above, numerous HE/VHE/UHE sources are also emitters of optical light. Many of them are variable. Astronomical photographic plate archives offer the only way to study the behaviour of

FIGURE 1. The largest European astronomical plate archive at the Sonneberg Observatory, Germany (280 000 plates). Left: original glass plates (negatives). Right: DVDs with plate scans (in addition to DVDs, the scans are stored on hard disks). The plate archive includes mostly sky patrol data for the whole northern sky hemisphere (above −20 declination) and hence any northern sky position is covered by large plates (typically 1–2 thousand).

FIGURE 2. Digitization of archival astronomical plates at the Sonneberg Observatory. Currently the Sonneberg Observatory is the place with largest number of digitized plates worldwide (more than 260 000 scans from 280 000 plates are available). The scans are performed using several commercial flatbed scanners.

these objects over very long time intervals (100 years or even more). In addition, the huge monitoring times provided by plate collections allow us to detect and study rare events such as flares, brightenings, and major light changes in general.

The importance of astronomical plates in HE/VHE/astroparticle astrophysics is obvious: they can provide supplementary observational data for objects with optical counterparts on:

- long-time evolution up to ≥ 100 years;

- flaring activity;

- in some cases, fine sensitivity (mag 20–23);

- in some cases, low-dispersion spectra (up to mag 18);

- in some cases, the ability to study short-term time variations $\sim$ mins;

- huge numbers of measurements: a typical plate has ~ 1 mil. objects, several millions of plates, $\sim 10^{12}$ data points;

- huge amounts of continuous monitoring of a particular object e.g. to detect rare flares (recently $\sim 26\,000$ h);

- the data is (almost) free of charge.

3. Historical optical light curves and binary black holes in blazars

This review focuses on the use of long-term data from astronomical plate archives for binary blazars. The features which can be investigated in very long-term optical light curves of blazars include: long-term periodicity in the light curve, detection of the quiescent level, detection of large-amplitude flares, etc. The features may be induced by underlying physical processes such as: the existence of supermassive binary black holes in blazars, stability, oscillations and changes of accretion disk, stability and changes in the jet, etc. However, the study of these features and processes requires either good long-term coverage of the optical light curve in history, or excellent coverage of a specific period in the past. An interesting field that requires good sampling of historical light curves is the theory of supermassive binary black holes, which are assumed to be harbored in some blazars.

Surely one of the most interesting blazars ever observed is object OJ 287, an easy target for both radio telescopes and optical telescopes. In 1988, Sillanpaa et al. [7] studied the optical light curve of this blazar and noticed a 12-year period within the major outbursts in optical light. The outbursts have a double peak structure with about one-year separation (the 12-year periodicity is neither strictly constant and nor is the separation of the peaks). Consequently, Sillanpaa et al. [7] predicted that the next outburst would come in 1994, and more recently, another outburst was predicted for 2006–2010 [9].

After the detection of the period in OJ 287, several models were suggested to explain the observed behavior. Most of these models assume that the engine of OJ 287 is a pair of supermassive black holes (however some non-binary black hole models have also been suggested). Sillanpaa et al. [7] assumed that the light variations are mass inflows from an accretion disk into the black hole, caused by tidal force of the secondary black hole. In the Lehto and Valtonen model [6], the outbursts are associated with the companion black hole crossing the accretion disk of the primary. Other

models followed – e.g. [8] modeled the behavior of OJ 287 starting from the Lehto and Valtonen model, while Katz [5] assumes that the secondary black hole exerts a torque on the accretion disk of the primary and thus causes the relativistic jet to sweep across our line of sight. Villata et al. [10] came up with a light-house model with a pair of bent jets. One of the latest established and investigated models was published by Valtonen et al. [9]. In this model, the features in the light curve are caused by 3 main processes: impacts of the secondary on the accretion disk of the primary, precession of the relativistic jet, and tidal influence of the secondary on the accretion disk of the primary. The double-peak giant flares occurring with a 12-year period are associated with impacts of the secondary black hole on the accretion disk of the primary. The long-term 60-year trend observed in the light curve results from the precession of the relativistic jet, which is caused by the influence of the secondary on the accretion disk of the primary. The tidal influence of the secondary on the accretion disk of the primary causes a variable accretion rate and thus a variable mass flow rate into the jet and a tidal outburst. Giant flares in 1947.3, 1973.0, 1983.0, 1984.2 and 1994.8 are used to construct a unique orbit solution. In this solution, the binary precesses by 33 degrees per revolution – the precession is caused by relativistic precession and leads to a loss of orbital energy due to gravitational radiation. The redshifted orbital period is 12.07 years, the mass of the primary is 1.77×10^{10} solar masses, the mass of the secondary is 1.3×10^8 solar masses, the major axis of the orbit is $0.056\,\mathrm{pc}$, eccentricity is 0.70. The inclination of the orbit is difficult to constrain with this model, but the steep rise of the outbursts led to the conclusion that the orbital plane is nearly perpendicular to the plane of the accretion disk. The next giant flares were predicted [9]. The newly recognized and previously unknown giant flare of the blazar in 1956, found by author of this paper (RH) on the Sonneberg archival sky patrol plates, was used for a precise prediction within the binary precession model. Moreover, theoretical reflections suggest that supermassive binary black holes may be common in the Universe. Direct and indirect observations show that supermassive black holes may be present in the center of nearby galaxies (e.g. [13]).

In the galaxy formation scenario, supermassive binary black holes should then result from mergers of galaxies which each harbor a supermassive black hole. The estimated number of supermassive binary black holes may be corrrespondingly high (e.g. [11]). However, this seems to be in contrast with observations. The explanation is that the orbital periods induced by the binary nature are of the order of thousands of years, which are timescales outside any observational records. Fortunately, there is a small region in the mass ratio/period plane (large mass ratio–short orbital periods) where binary black holes can be detected through periodic behavior [12]. Blazars seem
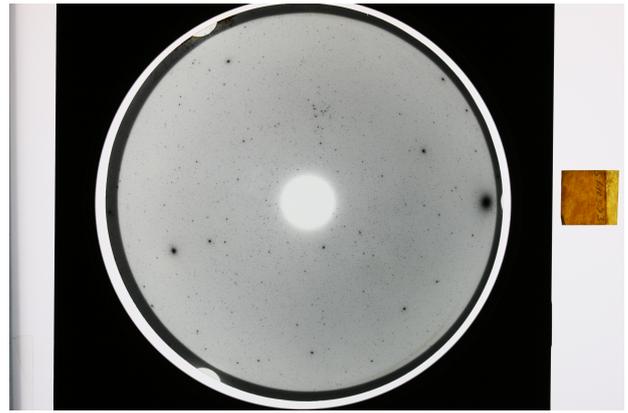

FIGURE 3. Example of digitized Baker Super Schmidt camera domed film (PARI astronomical plate archive). The number of films of this kind exceeds 100 000, and the time separation between two following exposures is typically only 20 minutes, so they are able to provide very dense light curves.

to be good candidates for detecting this kind of binary motion.

Hence, it may be feasible – with densely sampled long-term optical light curves – to find more blazars similar to the well-established supermassive binary black hole candidate OJ 287. This task can be addressed by continuing to gather observational optical data from the literature and from observational campaigns, in order to establish long-term optical light curves of blazars which are binary black hole candidates, and to study the periodic behavior in their light curves and other important features (major outbursts, flares, quiescent level behavior). However, there are still extensive data gaps that prevent us confirming the periodicity and/or a BBH model of these objects.

The obvious solution is to use the extensive databases of astronomical archival plates to fill in these gaps. The most valuable databases for these purposes are the sky survey (or field) program plates located e.g. at the following observatories: Sonneberg Observatory, Germany (about 280 000 plates), Harvard College Observatory, USA (about 500 000 plates), PARI Institute, NC, USA (more than 100 000 negatives), Bamberg Observatory, Germany (40 000 plates), the UKSTU plate collection, ROE Edinburgh, UK (18 000 very deep plates), and Leiden Observatory, the Netherlands (40 000 plates). Other plate archives can provide additional data for selected sources. Huge archival datasets that are little known to the astronomical community are located in various US plate archives. However it is very difficult to estimate the real number of acceptable plates, since they have not yet been catalogued [2].

The US plate archives include a very large number ($\geq 100\,000$) of very wide-field domed films taken by the Baker Super Schmidt camera with FOV of 55° diameter, limiting magnitude 14–15, and very dense time coverage (the time gaps between two consequent exposures is only 20 minutes). The Super
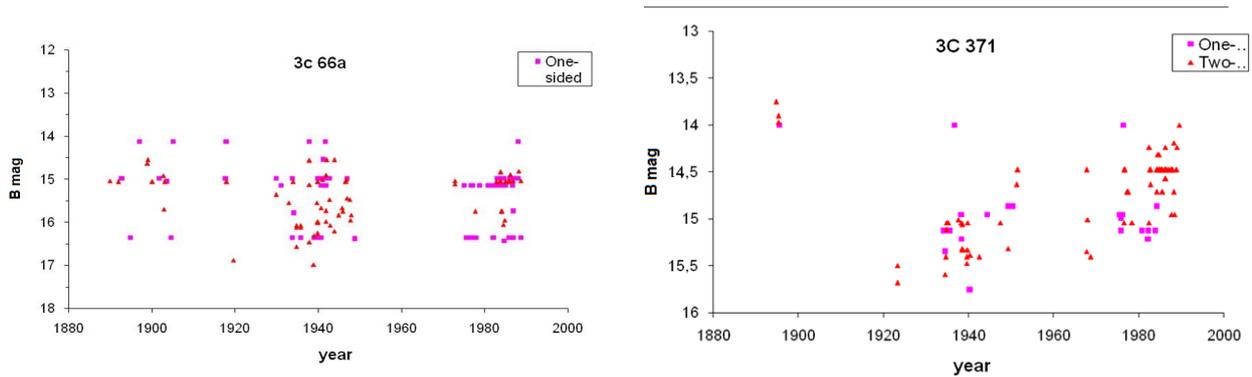
FIGURE 4. Left: 3C66a: Several flaring episodes, amplitudes ∼ 2–3 mag. Right: 3C371, four flaringepisodes revealed over ∼ 100 years, amplitude ∼ 2 mag. The overall long-term trend is also evident.

Schmidt camera was a catadioptric telescope system in which the spherical aberration of the concave spherical mirror was corrected by a complex combination of a Schmidt corrector plate and one or two meniscus lenses. The best-known system of this type is the super-Schmidt camera of J. Baker, in which two meniscus lenses that are concentric with the mirror almost completely compensate for the mirror's spherical aberration. The meniscus lenses do not disrupt the symmetry of oblique beams. The remaining spherical aberration is removed by an aspherical achromatized Schmidt corrector plate placed at the common center of curvature of the mirror and the meniscus lenses. The field of view of the Baker super-Schmidt camera is 55°, with a relative aperture of 1:0.67. The camera was originally used to take pictures of meteors (Fig. 3), but can also be used for photometry of astrophysical objects.

4. EXAMPLE OF PLATE ARCHIVE DATA MINING

We have identified several blazars as binary nature candidates, hence needing long-term optical photometry. The selected blazars were chosen after an extensive literature search, using the following criteria:

(1.) known or suspected periodicities in their light curves;

(2.) covered by archival plates, and being within their magnitude limit;

(3.) well-known blazars are preferred, as the gathered data can be used more widely by the scientific community. The complete list and further details are given elsewhere [4].

The extensive plate analyses performed at Harvard College Observatory (HCO) focused on data mining in the archival data with the aim to gather new historical data points for the following selected 9 blazars:

(1.) OJ287 (∼ 550 recorded data points);

(2.) 3c66a (∼ 400 recorded data points);

(3.) S20109+22 (∼ 450 recorded data points);

(4.) S50716+71 (∼ 450 recorded data points);

(5.) ON231 (∼ 500 recorded data points);

(6.) Mrk421 (∼ 550 recorded data points);

(7.) PKS2155−304 (∼ 550 recorded data points);

(8.) 3C371 (∼ 250 recorded data points);

(9.) BL Lac (∼ 150 recorded data points).

Examples of very long-term light curves (about 100 years) based on recent HCO data mining are presented in Fig. 4. It should be noted that the magnitudes of a non-negligible fraction of the sources were measured on plates with plate limits comparable to the brightness of the target.

More recently, tests were made on a transportable digitizing device based on a digital camera, for the purposes of fast plate scanning in plate archives where there is no scanning device. It is based on a 21 MPx Canon digital camera EOS 5D Mark II L, and Canon lenses EF 24–70 f/2.8 L USM & Canon 70–200 mm F4, a stable tripod, and a homogeneous light table. The device provides a fast (< 20 sec for one plate) and inexpensive (∼ $ 0.25) plate digitization technique, able to convert glass plates to computer files effectively. At the time of writing this paper further improved device is tested.

5. OTHER EXAMPLES OF HE/VHE/UHE SCIENCE WITH ASTRONOMICAL PHOTOGRAPHIC PLATE ARCHIVES

Besides long-term studies of binary blazar candidates, there are numerous other applications of long-term optical data in high-energy and very high-energy astrophysics. Examples of other applications are as follows: TeV blazars, gamma-ray binaries, GRBs, magnetars, etc. In addition, if the (new) PeV and EeV sources that will be detected with new instruments have persistent and/or flaring optical emission brighter than mag 20, then they can also be studied on astronomical archival plates.

Astronomical plate archives can provide very valuable data for studying Gamma Ray Bursts and related optical transients (OAs) and optical afterglows (OAs). There is a population of GRBs with bright prompt optical emission of GRBs. These OTs may achieve optical brightness of mag 6–12, and perhaps even brighter, lasting $\sim 1\,\mathrm{min}$, so it is obvious that these OTs can be recorded on astronomical plates. The obvious question is: how to find them? In addition, hypothetical orphan OTs and OAs can also be investigated on plates.

The recent Bamberg Observatory GRB project (see [3] for more details) can serve as an example:

- 5000 selected high-quality southern sky patrol plates investigated (by blink-comparison in pairs) for flaring GRB/OT candidates (including orphans);

- in total $\sim 50\,000$ square degrees covered for $> 24\,\mathrm{h}$, limiting magnitute 15–16;

- 6 candidates found, 2 promising — quiet candidates consistent with GRB host galaxy;

- an award winner in the Jugend Forscht German High School Competition in 2012;

- speculation: 1966 OT0519−5210 (one of the best candidates), the first ever recorded GRB? (first satellite detected GRB in 1967).

6. Conclusion

Astronomical photographic plate archives form a valuable data source for all optically variable sources, including HE, VHE and UHE objects. The most important applications of data mining in plate archives are as follows: long time evolution, dense sampling, rare flares, spectral and/or color changes.

Recent widespread digitization and the evolution of dedicated software have for the first time enabled evaluation by computer. In addition to widely-used flatbed commercial scanners and dedicated plate scanners, a fast ($< 20\,\mathrm{s}$) and inexpensive ($\sim \$\,0.25$) plate digitization technique has been developed and tested, which is able to convert glass plates to computer files effectively.

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