THE RADIO COLOUR–COLOUR DIAGRAM OF 
VAN DER LAAN BUBBLES — AN 
APPLICATION TO SS433

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Abstract

A radio "colour–colour" diagram is defined in order to determine the evolutionary state of synchrotron-emitting plasma bubbles that are ejected during outbursts in microquasars. We establish the colour–colour diagram for the plasmons of SS433 observed on 18 April 1998 using VLBI observations. We show that the radio plasmons are not consistent with a simple expanding sphere of plasmon. This may indicate that in-situ particle acceleration is taking place away from the central engine.

Keywords: stars: individual: SS433 – ISM: jets and outflows – radio continuum: stars

1. Introduction

Microquasars are galactic X-ray binary systems that contain a normal star and a neutron star or black hole. The former loses matter onto the compact object through an accretion disk. Part of this accreted matter leaves the system in

*This work has been carried out in collaboration with I. Fejes, R.C. Vermeulen, R.T. Schilizzi, R.E. Spencer and A.M. Stirling. Special thanks to Al Stirling for useful suggestions, István Fejes and Sándor Frey for careful reading. Financial support is acknowledged from the Hungarian Space Office (MÜH), the Netherlands Organization for Scientific Research (NWO) and the Hungarian Scientific Research Fund (OTKA, grant no. N31721 & T031723).
well collimated particle beams (jets), perpendicular to the disk. The nature of the compact object is still not known in several systems. How jets are formed, collimated, and how energetic electrons are produced in these relativistic beams are open questions. Most of these energetic electrons probably originate from the vicinity of the central engines of microquasars, but the Fermi-process (electron acceleration in shocks) within the jets may also play a role. Jet processes are briefly summarized by Spencer (1998).

An introduction to the Galactic radio-jet system SS433 as a microquasar and its high resolution properties determined in recent VLBI observations is given in Paragi (2001). The particular VLBI experiment shown here and the data analysis are described in Paragi (2000).

Below we introduce the Van der Laan (1966) model (originally developed for quasars) that describes radio emission from spherical plasmons ejected from the central engine during an outburst. The spectral index evolution of these ejecta from the optically thick to the optically thin regime is demonstrated on a radio colour-colour diagram. A spectral analysis of the radio components observed in SS433 follows.

2. Radio emission from spherically symmetric ejecta

Radiative properties of spherically symmetric ejecta depend on their instantaneous apparent size ($\theta$), the number density of relativistic electrons ($N$), and the strength of the magnetic field ($H$). The energy distribution of synchrotron radiating particles is $N(E) = KE^{-s}$, where $s$ is the energy spectral index. The emission and absorption coefficients of the synchrotron process have the following dependence on frequency: $j_\nu \propto \nu^{(1-s)/2}$ and $\kappa_\nu \propto \nu^{-(4+s)/2}$, respectively. The resulting spectrum is $S \propto \nu^\alpha$, $\alpha$ is the spectral index. In the optically thin domain the emission coefficient determines the spectrum, and $\alpha = (1 - s)/2$. In the optically thick domain the spectrum depends on the source function ($j_\nu/\kappa_\nu$), resulting in $\alpha = 2.5$.

The time evolution of the received flux density ($S$) in a radio outburst as observed at different frequencies was calculated by Van der Laan (1966). The effect of the optical depth ($\tau$) changing through different lines of sights in the source was considered by Hjellming & Johnston (1988). Their basic assumptions were that the ejected cloud of plasma expands adiabatically into the surrounding medium, and relativistic electrons are generated within a short time range close to the central engine, and not somewhere in the extended the jet. This latter assumption seems to be valid for microquasars (Spencer, 1998).
The time evolution of the flux density at four different frequencies is shown in Fig. 1. The plasmon brightens in the optically thick stage (until $\tau \sim 1$) with increasing radius ($\theta \propto t$ for free expansion), and there is an exponential cutoff in the optically thin regime. Of course $\tau$ has a strong frequency dependence, this is why the radio lightcurves peak at different times.

3. The radio colour-colour diagram

The model outlined above might be checked in multi-frequency observations by monitoring the total flux density of the sources during outburst. However, there may be several radio components contributing to the total flux, therefore it is desirable to have high resolution imaging experiments using the Very Long
Baseline Interferometry Technique (Zensus et al., 1995). VLBI observations are useful also because we can measure the size of the ejected plasmons, and this allows us to estimate the magnetic field strength. Even more information could be gathered if we could determine the optical depth of the component directly. In order to achieve this, we define a radio "colour–colour" diagram.

Similarly to Fig. 1, one might plot the spectral index evolution with time, starting from $\alpha = 2.5$ and eventually reaching $\alpha = (1 - s)/2$ (not shown). In practice we determine the spectral index between two observing frequencies as $\alpha_{ij} = \ln(S_i/S_j)/\ln(\nu_i/\nu_j)$ ($\nu_i > \nu_j$). It is straightforward that the high frequency spectral index versus the low frequency spectral index plot (the "colour–colour" diagram) will be model dependent, and contains information about the evolutionary state (i.e. the optical depth) of plasmons at these frequencies. The radio colour–colour diagram of a model outburst is compared to real measurements of SS433 in the next section.

4. Application to SS433

The source was observed at four frequencies on 18 April 1998, during a large flare. The VLBI map of SS433 at 5 GHz is shown in Fig. 2. There are four pairs of radio components, their ages range between $\sim 1 - 4$ days. We have the opportunity to observe plasmons of different age, i.e. in different evolutionary states even though the observations were made at a single epoch.

It can be seen from the radio colour–colour diagram (Fig. 3) that the plasmons of SS433 are already in the optically thin regime at these frequencies. Even the youngest component has $\tau_{10} \sim 0.1$. Other components have spectral indices that are not compatible with the model ($W_1$ is located outside the ranges shown). It seems that SS433 outbursts cannot be explained by spherically symmetric plasmons as described by Van der Laan (1966) – one or more model assumptions must be invalid.

One may speculate that the radio components seen are not spherical bubbles but shocked regions within the jet. In this case we expect to see significant degrees of linearly polarized emission, because shocks are ordering the magnetic field and the jets are near the plane of the sky (also, aberration is unimportant at the jet speed of 0.26c). We do not detect polarization in SS433 on VLBI scales. Unless there is an external Faraday screen depolarizing the source (to be investigated later), this means that the radio components seen on the maps are not single shocks.

There is one model assumption identified so far that is surely not true. We
have shown that the components are optically thin. But we are in the midst of a large flare in integrated flux density, and $S$ is expected to increase only in the optically thick regime. In order to increase the brightness of an optically thin source, relativistic electrons must be continuously produced – these particles are not supplied by the central engine in this case! Energetic electrons may be accelerated via the Fermi-process in shocks, but these shocks must be smaller than the components seen on the maps for two reasons: $i)$ we need several crossings through the shock in order to achieve an efficient acceleration (the smaller the shock the more effective the process is), and $ii)$ small shocked regions with different orientations of $H$ may cancel out the net polarization, resulting in a depolarized source as we observe.

5. Conclusions

We define a radio colour–colour diagram and demonstrate its applicability in analysing radio flares by comparing a model with the observations. There must be ongoing production of relativistic particles in order to explain the optically thin nature of the components and at the same time the increasing brightness of the source. This is clear evidence that in microquasars the central engine is not the only place where electrons can be accelerated to relativistic energies.
Figure 3: The SS433 radio components compared to the spherical plasmon model (solid curve). There are upper limits for $\alpha_{15-22}$ of some of the components that were not detected at the highest frequencies, $W_2$ was too faint even at 8 GHz, and $W_1$ lies out the ranges shown. The energy spectral index used in the model is $s = 2.2$

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