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Multi-Wavelength Jet Studies in Cataclysmic Variables and Super-Luminous Supernovæ

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Abstract. Astrophysical jets have been detected in objects as diverse as protostellar objects and supermassive black holes, yet we still have not answered the key question of what system properties are necessary to launch a jet. This talk described multi-wavelength time-domain studies to determine if two classes of objects at opposite ends of the energy scale are launching jets. First, Cataclysmic Variables (binaries with mass accretion rates of $\leqslant 10^{-8}\,\mathrm{M}_{\odot}\mathrm{y}^{-1}$) were previously thought *not* to launch jets, and have been used to constrain jet launching models. Nevertheless, recent radio observations have indicated a jet in one system, and have shown that that system is not unique. As regards the other end of the energy scale, we still do not know if the most powerful stellar explosions (Super-Luminous Supernovæ) launch jets. Recent improvements in sensitivity (particularly at radio wavelengths), higher-cadence transient surveys, significantly improved telescope response times and longer-term monitoring have led to substantial advances in these fields. The talk discussed how we are using multi-wavelength studies (with different cadences and coverage times) of these two extremely different classes of object to determine if they launch jets, thereby to constrain the properties necessary to do so.

Keywords. Stars: novæ, cataclysmic variables, stars: winds, outflows, stars: supernovae: general

1. Introduction

Jets are found in classes of accreting objects that have vastly different physical attributes and energies. Comparative studies of jets in objects with different properties (e.g., mass, magnetic field strength and accretion rate) constitute a powerful tool to constrain jet-launching and collimation models. The question of whether a particular class launches jets is thus important, but not always easy to determine. This talk discussed how we are using multi-wavelength observations to determine whether two classes of object with extraordinarily different energies and physical parameters are launching jets. Specifically, do Super-Luminous Supernovæ (the most powerful stellar explosions) and Cataclysmic Variables both launch jets?

2. Cataclysmic Variables

Cataclysmic Variables (CVs; Warner 1995) are binary stars in which a white dwarf accretes matter from a low-mass main-sequence companion via Roche-lobe overflow. Unlike the majority of accreting compact objects, CVs were previously believed to not launch jets (largely because, in early surveys, very few radio detections of CVs were made). Only three 'non-magnetic' CVs† (hereafter referred to simply as CVs) were detected prior to 2008 (Benz *et al.* 1989, 1983; Turner *et al.* 1985). Radio emission is the best tracer for jets, as it is comparatively uncontaminated with emission from other

† In 'non-magnetic' CVs, the magnetic field of the white dwarf ($<10^{6}$ G) cannot disrupt the accretion disk. See Barret *et al.* (2017) for radio observations of magnetic CVs.

components of the binary, such as the disk. The lack of radio detections of CVs therefore helped establish the idea that they did not launch jets‡. CVs have consequently been used to constrain jet-launching models in compact accretors (e.g., Soker *et al.* 2004).

However, the discovery of a possible jet in the CV SS Cygni (Körding *et al.* 2008) questioned the validity of using CVs as a control sample for jet-launching models. In X-ray binaries (XRBs, in which a neutron star or black hole accretes from a companion star) there is an empirical relation between the accretion and outflow properties (see Fender & Belloni 2012). Körding *et al.* (2008) showed that this relation could be mapped to CVs in outburst. In analogy to the XRBs, a transient jet should occur on the rise to outburst (a phase not previously observed) and produce a radio synchrotron flare. Such a flare was in fact detected and confirmed in multiple outbursts of SS Cyg, and various studies (Körding *et al.* 2008; Miller-Jones *et al.* 2011, 2012; Russell *et al.* 2016, Mooley *et al.* 2017) concurred that it is best explained as synchrotron emission from a transient jet. One more CV was subsequently detected at radio wavelengths (Körding *et al.* 2011), but it was only after the sensitivity upgrade of the Very Large Array (VLA) that CVs as a class were proved to be radio emitters (Coppejans *et al.* 2015, 2016).

Nine CVs, comprised of five outbursting (dwarf novæ) CVs and four nova-like CVs: U Gem, SU UMa, YZ Cnc, RX And, Z Cam, RW Sex, V1084 Her, TT Ari and V603 Aql, were observed with the VLA at ∼4–12 GHz (Coppejans *et al.* 2015, 2016), of which eight were detected in action. The specific radio luminosity at 10 GHz was in the range $L_{10} \sim 4 \times 10^{15}to4 \times 10^{16}$ erg s^{-1} Hz^{-1}, and variability on time-scales of ∼200 s to days was recorded. There was no correlation between the radio luminosity and optical luminosity, orbital period, orbital phase or CV class, but that might be masked by the variability. The spectral indices were largely unconstrained, and most of the sources showed upper limits to the circular and linear polarization fractions of ∼10%. TT Ari, however, showed a ∼10–minute flare with a polarization fraction of >75%, consistent with cyclotron-maser emission. The emission from the rest of the CVs was consistent with synchrotron or gyrosynchrotron emission.

The emission from the CVs observed in radio was consistent in luminosity and variability time-scales with that of SS Cyg, but the signature radio flare has not been detected in any other CVs to date. Higher-cadence observations of the rise phase are necessary to confirm or rule out such flaring. CV outbursts are not periodic, and the rise phase lasts approximately 24 hours. To catch that phase, Coppejans *et al.* (2016) triggered radio observations through an optical monitoring campaign with the AAVSO observers. The MeerKAT key science project ThunderKAT (Fender *et al.* 2017), in combination with the optical telescope MeerLICHT (Bloemen *et al.* 2016), will offer a powerful new tool for these studies. They will provide simultaneous optical and radio observations, while ThunderKAT has dedicated time for CV science and also commensal access to data from the MeerKAT large surveys. Those will support statistical studies of large samples of CVs through the use of archived data. CVs are nearby, numerous, show a range of accretor properties (e.g., accretor mass, accretion rate and magnetic field strength) and are non-relativistic. If CVs launch jets, then they are an ideal target for jet studies, as the effect of the accretor properties on the jet can be studied directly in the absence of relativistic effects.

3. Hydrogen-Poor Super-Luminous Supernovæ

Super-Luminous Supernovae (SLSNe) are a sub-class of core-collapse supernovæ (SNe) that are typically ∼10–100 times more luminous than their counterparts, with UV–optical luminosities $L > 7 \times 10^{43}$ erg s^{-1} (e.g Quimby *et al.* 2011; Chomiuk *et al.* 2011).

‡ Jets have been found in other white dwarf accretors, namely in novæ and the symbiotic stars (e.g Brocksopp *et al.* 2004; Sokoloski *et al.* 2008)

The reason for the high luminosities is not yet understood. For the hydrogen-rich SLSNe (SLSNe-II) the enhanced luminosity is chiefly attributed to interaction with a dense circumstellar medium (e.g., Smith *et al.* 2007). For the hydrogen-poor SLSNe (SLSNe-I), however, there are three competing models. (a) Interaction with a dense circumstellar medium is possible, but the narrow emission lines that would indicate it are not observed (see however Yan *et al.* 2015 and Roth *et al.* 2016). (b) Larger quantities of radio-active material would increase the luminosity (e.g., Woosley 2007; Gal-Yam *et al.* 2009), but few viable candidates for such a model are known (e.g., Terreran *et al.* 2017). (c) Additional energy could be injected via a central engine such as the spin down of a magnetar (e.g., Kasen & Bildsten 2010; Woosley 2010; Nicholl *et al.* 2013; Metzger *et al.* 2015), or accretion onto a black hole (Dexter & Kasen 2013). Here we focus exclusively on the third mechanism.

Jets are key manifestations of central engines, and are most effectively observed at radio and X-ray wavelengths as they are produced by relativistically moving material (in contrast to thermal optical emission from the slower SN ejecta). To date, no detection of a SLSN-I has been made at radio frequencies, but the upper limits provide an effective tool to constrain the properties of jets and the surrounding medium. Coppejans *et al.* (2017) compiled all the radio limits of SLSNe-I to date and included three new limits†.

Radio-jet light-curves are affected by various properties: the angle between the observer and the jet-axis (the 'observer angle'), the environment density, the micro-physical shock parameters ϵ_B and ϵ_e‡, the opening angle, and the kinetic energy. The jet emission is initially highly beamed, but spreads as the jet slows and the radiation becomes less beamed. Off-axis observers at larger angles will consequently see the emission at later times.

Coppejans *et al.* (2017) ruled out highly collimated on-axis jets in SLSNe-I of the kind seen in Gamma-Ray Bursts (GRBs), through a direct model-independent comparison of the light-curves of the two systems. To constrain off-axis jets, we modelled the ∼GHz-frequency light-curves using 2-dimensional relativistic hydrodynamical jet simulations for a grid of properties, and constrained them at the observed upper limit. We showed that, regardless of observer angle, if highly-collimated GRB-like jets were present, they would have energies of $<4\times10^{50}$ erg and would be in environments shaped by progenitors with mass-loss rates of $<10^{-4}\,\mathrm{M_{sol}y^{-1}}$ (for microphysical shock parameters of $\epsilon_\mathrm{e}=0.1$ and $\epsilon_\beta=0.01$). That density is similar to, or lower than, the environments of GRBs. The mass-loss rate excludes winds of the kind observed in extreme red supergiants and luminous blue variables. Coppejans *et al.* (2017) give the constraints on the full grid of jets parameters and uncollimated outflows.

The key to monitoring SLSNe-I for jet signatures is through a combination of fast responses (within days of the SN explosion) and long-term monitoring (hundreds of days) at radio and X-ray wavelengths. The former criterion is difficult to achieve owing to the time it takes to classify SLSNe. The latter point is crucial for constraining off-axis jets, which are observed later. Higher-sensitivity radio observations from telescopes such as MeerKAT will enable us either to detect SLSNe-I or to provide deeper upper limits for answering the question as to whether these systems launch jets.

4. Conclusion

Despite vast differences between CVs and SLSNe-I in energy and physical properties, we are trying to answer a question common to both: do they launch jets? It is still not clear what physical properties are necessary to launch a jet, but observations of different classes of sources are a powerful means to clarify that. Multi-wavelength observations

† For an analysis based on all the X-ray observations of SLSNe-I, see Margutti *et al.* (2017)
‡ ϵ_B and ϵ_e are the post-shock energy fraction in the magnetic field and electrons, respectively

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with carefully chosen timing and cadences are necessary to probe the presence of jets in these objects. The advances that are planned for radio telescopes, in particular, over the next few years will lead to significant progress in determining which classes of objects launch jets, and why.

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