X-RAY BINARIES

Gamma-ray echoes from SS 433

A periodic gamma-ray signal detected from the micro-quasar SS 433 cannot be associated with its jet. Instead, a new mechanism capable of channelling most of SS 433’s kinetic power to large distances is needed to explain the observations.

Pol Bordas

Only two X-ray binary systems (XRBs) displaying relativistic jets, Cyg X-1 and Cyg X-3, have so far been confirmed as high-energy gamma-ray emitters. Gamma rays are thought to be produced close to the jet base, where the ambient matter and radiation fields are the highest and processes like inverse Compton and proton–proton interactions can efficiently produce the observed fluxes. Writing in *Nature Astronomy*, Jian Li and collaborators present the surprising discovery that a third accreting XRB, SS 433, is also producing gamma rays, but the emission is in this case resolved into several components, one of which displays significant periodicity and is located 36 parsecs away from the central binary system.

The micro-quasar SS 433 is beyond doubt a flagship of XRBs. It is composed of a compact object, most probably a black hole of 10–20 solar masses ($M_\odot$), orbiting a 20$M_\odot$ supergiant star every $P_{\text{orb}} \approx 13$ days. The supergiant feeds the compact object at a rate of $10^{-4}M_\odot$ per year through the formation of an extended accretion disk that precesses under the pull of the secondary star every $P_{\text{pre}} \approx 162$ days. SS 433 stands as the only supercritical accretor known in our Galaxy; it has an unparalleled energy budget delivering more than a million times the Sun’s luminosity, and is identified as a true cosmic-ray factory and the sole case in which protons are detected in relativistic jets. Since its discovery, SS 433 has been a unique laboratory for high-energy astrophysics, shaping our knowledge on XRBs and the mechanism through which accretion-powered jets are produced.

The first claims for the detection of gamma-ray activity towards SS 433 came in 2015 after the analysis of about five years of data taken with the Fermi Large Area Telescope (LAT) satellite. Gamma-ray emission with a spectral energy distribution peaking at a few hundred MeV was detected from a region encompassing SS 433 and the surrounding W50 nebula (Fig. 1). No signs of flux variability were seen, suggesting that gamma rays were produced at the SS 433/W50 interaction regions. Follow-up studies at high energies found a tentative extended nature for the gamma-ray source and also provided some hints of variability compatible with the precession period of the accretion disk. Monitoring observations conducted with the High Altitude Water Cherenkov array resulted in the detection of gamma rays from the east and west ‘lobes’ of SS 433/W50 at energies above 25 TeV (ref. 11). This is the first and so far only confirmed case of gamma-ray emission detected from jet-inflated bubbles in our Galaxy.

Using a larger Fermi LAT data set and the latest source catalogues and models for the Galactic diffuse emission, Li and collaborators consider in detail the strong contamination from the bright and nearby pulsar PSR J1907+0602, a key factor in reducing potentially severe spectral and...
morphological systematic effects. Employing the latest ephemeris for this pulsar, each recovered gamma ray is imprinted with information on PSR J1907+0602's rotational phase. Selecting only off-peak intervals in their data set, the results of this ‘gating’ analysis have revealed that gamma rays are produced relatively far from the position of the central binary system and are composed of several components. On the one hand, steady gamma ray emission is recovered from a source spatially coincident with the western terminal jet lobe. On the other hand, a new variable component has emerged, named Fermi J1913+0515 (also shown in Fig. 1), displaying a periodic modulation with a statistical significance of 3.5σ at a period of ~160 days. This periodicity is compatible with the precession period of SS 433, but with an important caveat: the emitter seems to be located ~36 parsecs away from it.

Theoretical predictions of variable gamma-ray emission based on the periodic changes of the conditions of the medium around the central system therefore seem to be ruled out. Li and collaborators report, however, on the presence of dense clouds of atomic gas, with a mass of about 25,000M⊙, in SS 433’s surroundings that are spatially coincident with this variable gamma-ray component. Gamma rays could therefore have a hadronic origin, following the interaction of relativistic protons flowing along SS 433 jets against target material from the clouds. But once more, gamma rays cannot be the product of the illumination of these clouds by the jets, since these propagate along directions incompatible with the location of the gamma-ray excess. Intriguingly, and against all expectations, the observed variable gamma-ray component may not be related to SS 433 jets after all.

The supercritical accretion regime operating in SS 433 not only creates powerful jets, though, it also releases large amounts of kinetic energy through the creation of equatorial relativistic outflows or winds produced at the surface layers of the accretion disk. Such a high kinetic power and the geometric inclination of the disk-wind envelope and its relatively wide solid angle, amplified by precession, prompts Li and collaborators to suggest this wind as an additional power source from SS 433 that could be illuminating the gas clouds. In order to keep periodicity, however, relativistic protons should regularly arrive at the cloud at a sufficient rate. For a gamma-ray luminosity at a level of Lγ = 1034 erg s⁻¹ and a cloud density of n = 20 cm⁻³, an energy reservoir in protons of Wp = 2.5 × 10³⁹ (Lγ/10³⁴) (n/20) erg is needed. The kinetic power in the wind is of the order of Lkin ≈ 10³⁸ erg s⁻¹, so about 100 years of continuous injection would be needed. Such a relatively large time would, however, remove the ~160 days periodicity. The only way to circumvent this problem, both from an energetics basis and to explain the observed phenomenology, is to assume a local enhancement of the cloud density (a cusp with a ≳ 10³ rd cm⁻³) and to postulate a mechanism capable of periodically delivering about 10% of the whole SS 433 kinetic power in relativistic protons for about half of its precession cycle and placing them right at the location of the cusp. On theoretical grounds this seems unachievable. Not only is a rather efficient acceleration mechanism needed to get ~0.1Lγ in relativistic protons, one also needs to funnel all this power towards the cloud, located 36 parsecs away, through some unknown streaming mechanism that connects it with the azimuthally isotropic and hence rather uncollimated disk-wind envelope.

More than 40 years after its discovery, SS 433 keeps providing remarkable observational and theoretical challenges for the high-energy astrophysics community. The gamma-ray band wasn’t going to be an exception, and the detection of emission from the jet lobes and the presence of a new periodic gamma-ray signal tens of parsecs away from the central system are beyond any previous expectation. Additional observations at this energy band, particularly with the forthcoming Cherenkov Telescope Array observatory, will provide further insights into the high-energy processes taking place in SS 433. In parallel, the development of a new framework providing theoretical support for efficient particle acceleration and anisotropic diffusion of relativistic winds from accretion disks is still to be forged out.