"Magnetically Arrested Disk" Revealed by Multiwavelength Observation

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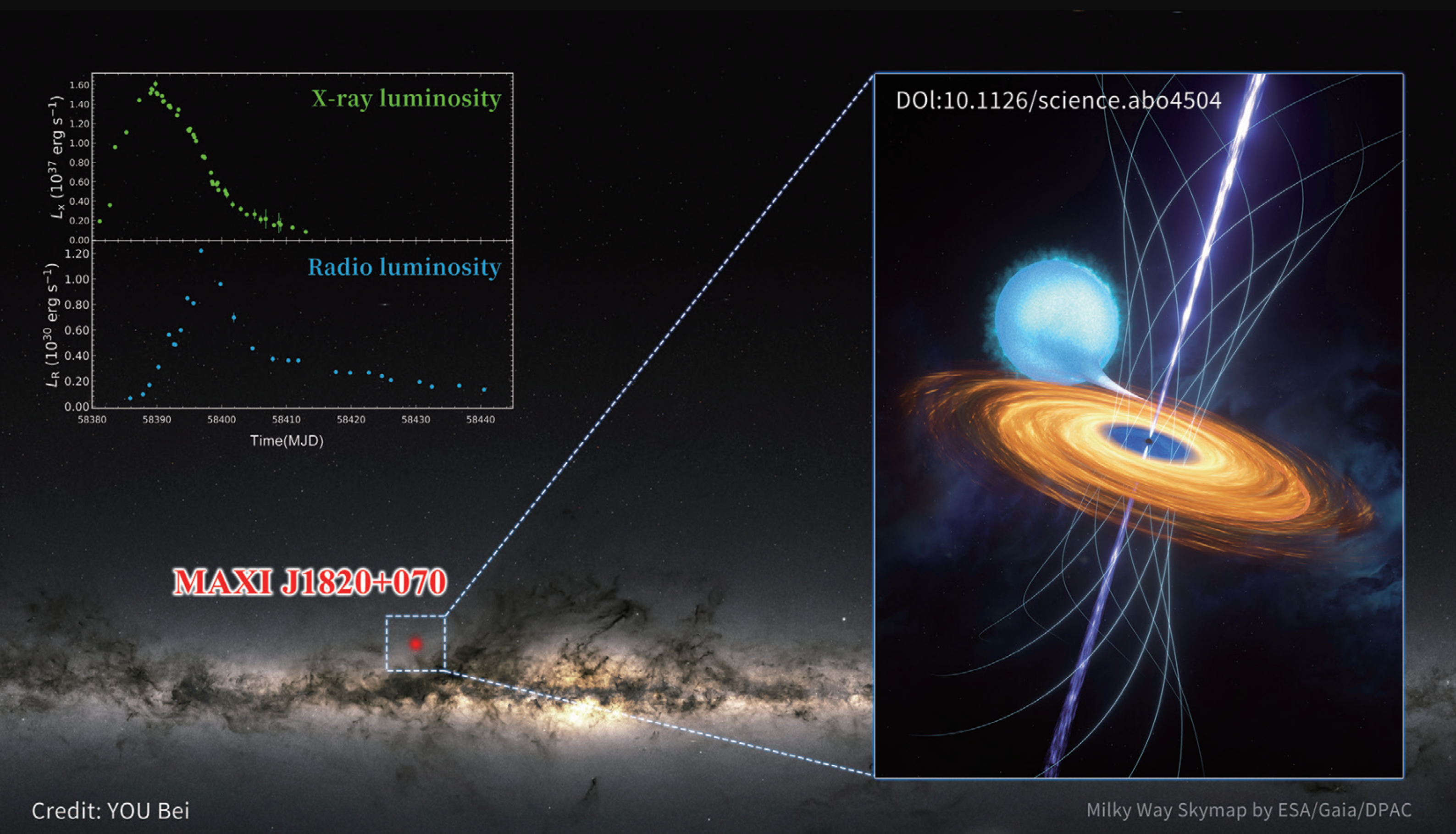


An international team of astronomers detected time delays in radio and optical fluxes in comparison with X-ray flare observed during the 2018 outburst of a black hole binary, when analyzing the datasets obtained by the Insight-HXMT of CAS and other instruments. (Image by YOU B)

An international team of astronomers discovered delays in radio and optical fluxes from a black hole (BH) binary – about 8 and 17 days respectively – compared with the X-ray outburst from the same object. These delays, as explained by the authors, can be interpreted as evident formation of a magnetically arrested disk (MAD), a scenario predicted by a theoretical model that has long sought observational evidence for support.

Led by Prof. YOU Bei from the Wuhan University, Prof. CAO Xinwu from the Zhejiang University, and Prof. YAN Zhen from the Shanghai Astronomical Observatory of the Chinese Academy of Sciences (CAS), the work was conducted by a joint team pooling research forces from the Institute of High Energy Physics and University of Science and Technology of China under the umbrella of CAS, and oversea institutions including the Astronomical Observatory of Strasbourg in France and the Center for Theoretical Physics, Polish Academy of Sciences of Poland.

The joint team found the delays when analyzing the archival multi-wavelength observations on the outburst from the X-ray binary (labelled MAXI J1820+070) in 2018, and reported their result in *Science* on September 1.

The target binary contains a stellar-mass BH and a normal low-mass star, with the latter orbiting the former. The BH, with its formidable gravity field, sucks up the matter from its companion star, and hence forms an accretion disk featuring hot plasma inflows. When the charged, rapidly moving material is being drawn to the BH, the magnetic field carried by the inflow itself also moves onto the BH. However, according to a theoretical model, when the BH magnetic field strengthens, the magnetic force along its radial direction can mount onto a threshold as large as its gravity in the opposite direction along the radius, hence halting the accretion inflow itself. In this scenario, the accretion disk seems to be arrested by the magnetic force to form a slowly falling disk, namely the MAD.

The formation process of such a MAD has not been observed, however, though the model predicts that this scenario can manifest in either accreting supermassive or stellar-mass BHs.

Thanks to the synergic observations joining the Hard X-ray Modulation Telescope (Insight-HXMT) of CAS, a satellite working in hard X-ray wavebands to stare into celestial objects, and ground-based radio and optical observatories, scientists are now able to combine signals from different wavelengths of the same object to better understand the process of the accretion.

First the team established the X-ray profile of the object based on the dataset obtained during the outburst of the binary in 2018 by the Insight-HXMT. The data cover a broad energy band from 1 to 250 keV and span a timeline as long as seven months extending from 14 March 2018 to 21 October 2018.

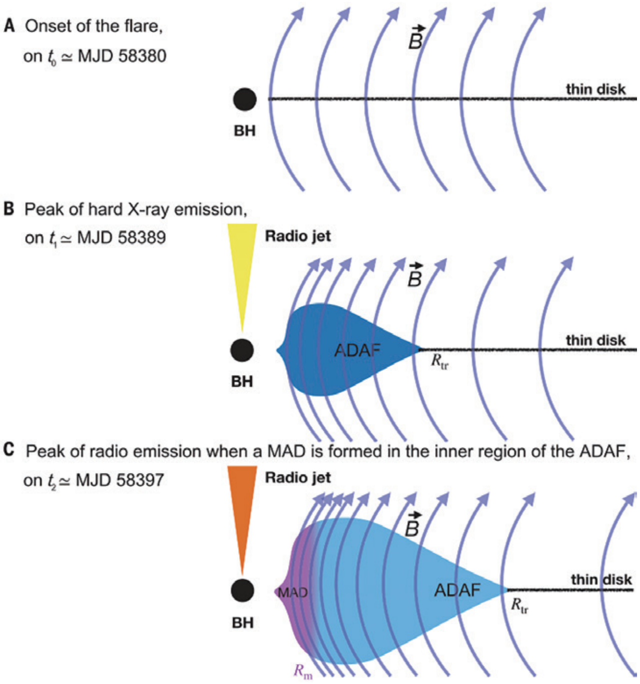
The outburst of MAXI J1820+070 also produced bright optical and radio signals to be picked up by ground optical/radio telescopes. The American Association of Variable Star Observers (AAVSO) monitored this outburst, and produced a light curve spanning from 12 March 2018 to 21 December 2018. Meanwhile, the radio emission from the same object was detected by multiple telescopes. Among them the team chose the radio flux recorded by the Arcminute Microkelvin Imager Large Array (AMI-LA) to perform their analysis.

Altogether, these datasets offered highly enriched profiles of the object's 2018 outburst over a broad range of wavelengths. Analyzing the object in different wavebands, the team tried to identify the lags between flares at different bands.

To determine the time lag between the radio and X-ray flares, the team performed an interpolated cross-correlation function (ICCF) analysis to the datasets. They found that the radio lag was about 8 days compared with the X-ray flare. ICCF analysis comparing the optical and the X-ray datasets showed that the optical flare came 17 to 18 days later than the X-ray one, marking a delay far longer than the time taken for light to travel across the binary system.

According to the lag between X-ray and radio peaks, the team analyzed that the radio emission originated from the jet, and the hard X-ray emission has come from the gaseous corona close to the BH event horizon. The X-ray emission depends not only on the mass accretion rate but also the corona size. Meanwhile, the magnetic field of the outer thin disk is dragged inwards with the corona, which produces the jet and emits the radio emission.

Given that the continuously increasing magnetic force acting on the inflows competes with the gravitational force from the BH itself, the accretion would be halted



The team explains the delay in radio fluxes compared with X-ray burst with the illustration. (Image by YOU B)

with slowly inflowing velocity when the two forces are comparable to each other. Calculation showed that the time lag of radio flare behind the X-ray can be explained by the accretion model that predicts the occurrence of a MAD: when the hot gases close to the event horizon accumulates due to the slowing down accretion, the corona expands and stands to form a MAD.

The optical delay, however, cannot be predicted by the existing standard disk instability model (DIM) very well. The team hence speculated that the X-ray flare could have caused "disk instability" in the accretion inflow to emit photons in the accretion disk – the source of the optical flare. Starting from the idea, they fitted a modified DIM model that better explains the 17-day delay between the optical peak and the X-ray flare.

"Using a simple parametrization of the disk wind, we performed additional simulations of the DIM. We found that the resulting *V*-band flare is consistent with the observed light curve, lagging the hard X-rays by more than 15 days," said the authors.

Reference

You, B., Cao, X., Yan, Z., Hameury, J. M., Czerny, B., Wu, Y., . . . Zycki, P. T. (2023). Observations of a black hole x-ray binary indicate formation of a magnetically arrested disk. *Science, 381*(6661), 961-964. doi:10.1126/science.abo4504