DISCOVERY OF THE OPTICAL COUNTERPART OF THE X-RAY NOVA GRO J1655-40

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Abstract

A new X-ray nova was discovered in July 1994 by the Compton Gamma Ray Observatory, and was designated GRO J1655-40. Our group at Yale promptly discovered the optical counterpart. Radio observations of the optical counterpart detected jets expanding at relativistic speeds.

1. Introduction to X-ray novae

The X-ray novae are binary systems in which the compact primary star accretes material from a companion star, which is often a late-type main sequence star. The accreted material from the companion star forms an "accretion disk" around the compact object. The material slowly makes its way towards the center of the disk, where it falls into the gravity well of the compact object, giving off a large amount of energy in the process. The amount of accretion energy depends on the mass and radius of the compact object—accretion onto objects with high mass and small radii produce the most energy. The accretion luminosity is also proportional to the mass accretion rate. In the case of accretion onto a neutron star or black hole, most of the energy produced is in the form of high energy X-rays. Accretion onto a white dwarf will produce energy mostly in the extreme ultraviolet and low energy X-ray region of the electromagnetic spectrum. One can show that the compact objects in the X-ray novae must either be neutron stars or black holes to account for the luminous high-energy X-rays.

An X-ray nova usually spends most of its time in a state in which the accretion rate is very small. Hence the accretion luminosity is very small, and the system is usually invisible in X-rays. Sometimes, however, an instability in the accretion disk will result in a large increase in the accretion rate, which results in a dramatic increase in the X-ray luminosity (an increase in the X-ray luminosity by a factor of one million is not uncommon). Within the period of a few days, the system will go from being invisible in X-rays to becoming the brightest X-ray source in the sky (hence the term "X-ray nova"). These X-ray outbursts take place approximately every 50 to 100 years and last for several days to a few weeks. After a few months or less, the X-ray luminosity drops rapidly to its quiescent level, where the system once again becomes invisible (or nearly so) in X-rays.

The secondary star in the X-ray nova can be observed during the long quiescent interval (this is usually not the case in most low mass X-ray binaries, where the accretion luminosity is many orders of magnitude greater than the luminosity of the secondary star). Spectra of the companion star can be used to track the orbital velocity of the secondary star, which in turn can put a strict lower limit on the mass of the compact object. In several X-ray novae, it has been shown that the mass of the compact object is in excess of three solar masses, which is the maximum mass that a neutron star can have within general relativity (Chitre and Hartle 1976). These objects must therefore be black holes. Thus X-ray novae provide the best evidence for the existence of stellar-mass black holes in nature (Cowley 1992), and are therefore important systems to study.

2. Detecting X-ray novae and identifying optical counterparts

Many of the X-ray satellites in Earth orbit have "all-sky monitors" (ASMs). These instruments can observe nearly the entire sky in a few hours. An X-ray nova in outburst can become one of the brightest X-ray sources in the sky, and any new X-ray nova in outburst will quickly be discovered by the ASMs in orbit. However, due to the nature of an ASM, the position of a source cannot be accurately determined. The source position typically has an "error box" of nearly a square degree on the sky. Thus we must rely on optical and/or radio observations to identify which star in the sky is the X-ray nova. Since the period of high X-ray luminosity lasts only a few months, we must act quickly.

Not all of the energy produced in the X-ray outburst will be in the form of X-rays. Large amounts of energy are also produced in the UV, optical, and radio bands. Thus we expect to see a coincident optical nova associated with the X-ray nova. The name of the game is to identify an optical nova near the position of the X-ray nova and to show that the two objects are associated. If the decline of the optical nova over time tracks the decay of an X-ray nova over time, this is a strong indication that the two objects are the same. Also, the optical spectrum of an X-ray nova in outburst shows high excitation emission lines of hydrogen, helium, nitrogen, and carbon, further evidence for the presence of an energetic process (which in this case is the accretion onto the compact object). "Ordinary" variable stars will not show such a spectrum. The optical counterparts also can be bright in the U and B optical bands, but the exact optical colors depend on the amount of interstellar dust between us and the object (i.e., the reddening).

3. The optical counterpart of GRO J1655-40

A new X-ray source was discovered on July 27, 1994, with the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory. This source was designated GRO J1655-40 (after its approximate 2000 coordinates in the sky—the numbers refer to the right ascension and declination). On August 4, 1994, the BATSE team announced their discovery (Zhang *et al.* 1994). It so happened that Yale had two and a half weeks of observing time scheduled on the 0.9-meter telescope at Cerro Tololo Interamerican Observatory (CTIO), located in Northern Chile. This long block of time was scheduled to begin the day after the discovery of GRO J1655-40 was announced. The observers in Chile were Charles Bailyn and Shardha Jogee. I stayed in New Haven.

The error box around the reported position of GRO J1655-40 was relatively small, slightly larger than a half a degree on a side. The only detector available for the 0.9-meter telescope is a CCD chip with 2048 pixels on a side. The field of view of this particular detector/telescope arrangement is 14 arcminutes by 14 arcminutes. Thus it would be possible to image the entire error box of GRO J1655-40 using "only" nine exposures.

To find an optical nova (i.e., a star which brightened significantly in a short period of time), we need to compare recent images of the sky with archival images of the sky. The Palomar Sky Survey prints are an example of such an archive for the northern sky; the European Southern Observatory (ESO) survey is the equivalent archive for the south. However, these prints cover a large area on the sky (usually six by six degrees) and contain hundreds of thousands of stars. It is very difficult to compare a CCD image of a relatively small part of the sky with the equivalent region on a large sky survey print. Fortunately for us, there was an easier way. The Space Science Telescope Institute has published an all-sky survey in digitized form (available on a series of CD ROMs). Digitized images (of any size) may be extracted and viewed with the same software that is used to view CCD images. These digitized V-band images are complete down to about V=19 or 20, which makes them ideal for this purpose.

CTIO is connected to Yale via the Internet. Charles sent me electronic mail telling me about the discovery of GRO J1655-40 the night before the scheduled observing run. I extracted nine images from the digitized sky survey, each one 14 by 14 arcminutes. The centers were 12 arcminutes apart, and when arranged in a three by three grid, covered the error box around the X-ray nova position (as determined by the BATSE instrument). I sent the grid coordinates and the images to Charles and Shardha shortly before they were scheduled to start observing.

The weather in Chile was very bad for the first three nights of the observing run. There was snow on the first night, heavy fog on the second night, and thick clouds for the third night. The domes on CTIO stayed closed for the first three nights, and the observers occupied themselves by watching videos and by playing volleyball in the 4-meter dome. The fourth night started out bad, but then cleared up enough to allow for some observations. Charles and Shardha were able to get the three southern-most images on the grid (using five-minute exposures in V). These images were sent electronically to a computer at Yale, where I carefully compared them to the digitized sky survey images of the same fields. I quickly discovered what Galileo had discovered in 1610: there are a huge number of stars towards the galactic plane! In order to carefully inspect the CTIO images, it was necessary to "zoom in" on subsections of the image in order to compare it with the sky survey images, which was not difficult to do. Thus the task of comparing the CTIO images with the digitized sky survey images was straightforward, but it was also time consuming and tedious.

I found no evidence of an optical nova in the first three images. The next day, we received electronic mail from the BATSE team. They had refined the position of GRO J1655-40. The revised right ascension was the same, but the revised declination was 18 arcminutes to the north. We were looking in the wrong spot! I therefore extended the search grid by adding three images directly north of the origional grid. That night was clear in Chile, and Charles and Shardha sent me nine more images. I spent most of the next day carefully comparing the CTIO images with the sky survey images. I found nothing new, and I was quickly becoming discouraged. The new error box around the position of GRO J1655-40 extended a few arcminutes north of the northern part of our grid, so I again extended the grid by adding three images to the north. I sent Charles and Shardha the coordinates and finding charts for the three newest fields, and I had the images later that night. The next day, I did a quick look at the three new images and saw nothing new. I made one last attempt to locate an optical nova. I carefully went through all fifteen images in the order that they were taken. Only one fourth of an image was looked at at one time, giving a total of sixty fields to search.

I finally found an optical nova in the last image that was taken. The star in question was approximately V=14.5 on the CTIO CCD image, while it was fainter than about V=17 on the digitized sky survey image. These images are reproduced in Figures 1 and 2. This star was the only star in the 15 images which showed any significant increase in brightness. Also, the newly discovered optical nova was bright in a narrow band filter centered on the hydrogen Balmer alpha line (relative to the other field stars), an indication of an unusual spectrum. Unfortunately, there were no spectrographs available at CTIO during that time, so we could not get spectroscopic confirmation that the optical nova was likely to be associated with GRO J1655-40. On August 11, we announced our discovery and asked for spectroscopic confirmation (Bailyn, Jogee, and Orosz 1994). Massimo della Valle obtained a spectrum from ESO the following night (della Valle 1994). This spectrum showed strong emission lines of hydrogen, helium, and nitrogen, providing clear evidence that the optical nova was associated with the X-ray source GRO J1655-40.

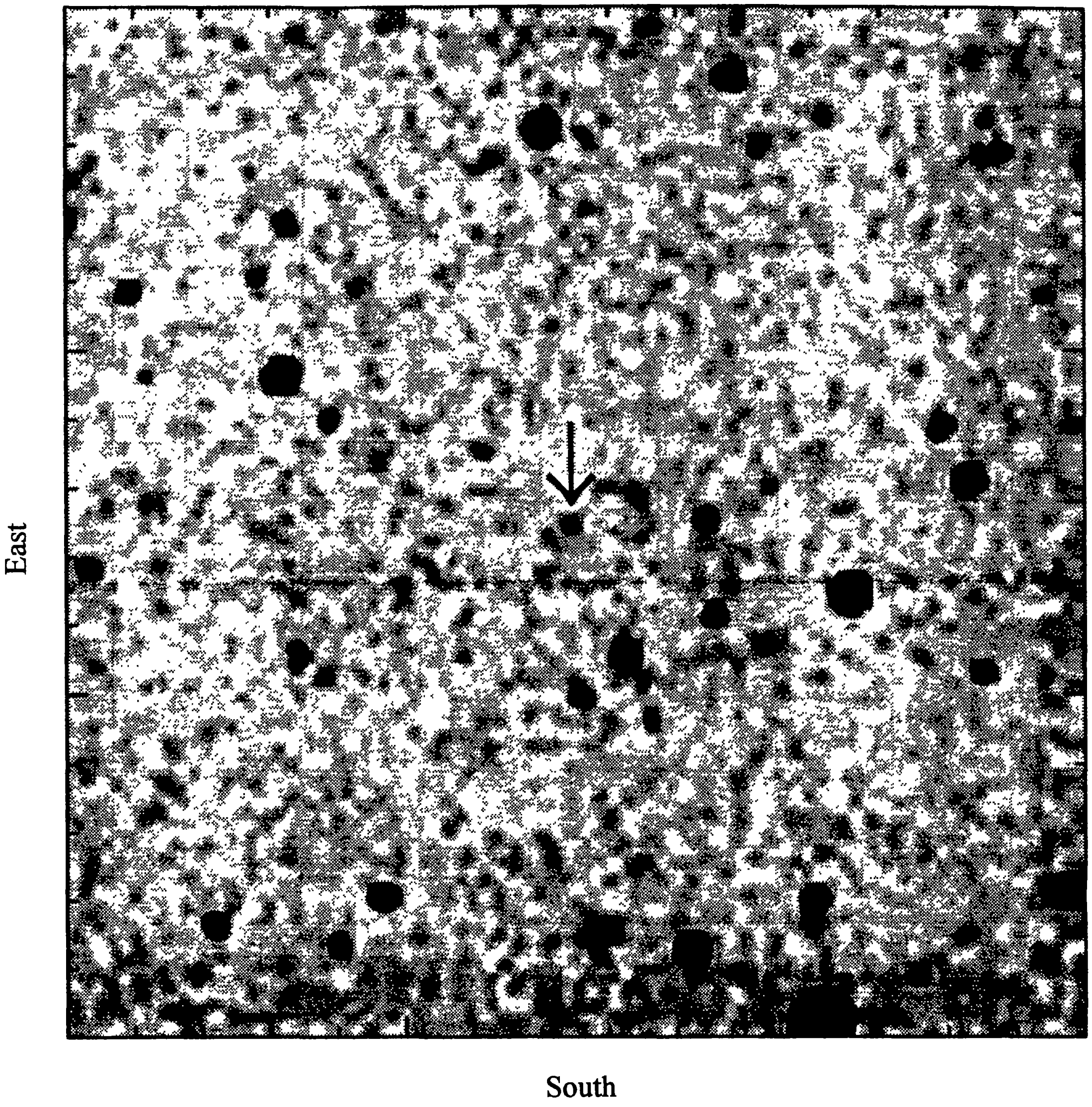

Figure 1. A three arcminute by three arcminute area of the sky, taken from the UK Schmidt digitized sky survey, April 4, 1988. The image is negative, so the stars appear as dark spots. The optical counterpart of GRO J1655-40 is marked with the arrow.

4. The importance of GRO J1655-40

About the same time we located the optical counterpart to GRO J1655-40, a strong radio source was identified near the position of the optical nova (the preliminary radio position was within five arcseconds of the preliminary optical position, well within the errors expected from converting from the radio coordinate system to the optical coordinate system). This radio source grew stronger in the following week, something which is unusual for X-ray novae. The source was then observed with the Very Large Array (VLA) and the Very Large Baseline Interferometer (VLBI) radio telescopes. These radio telescopes are capable of obtaining radio maps with very high resolution (better than a few milliarcseconds for the VLBI). These high resolution maps showed the evolution of rapidly expanding jets. The bulk motions in these jets had a velocity of

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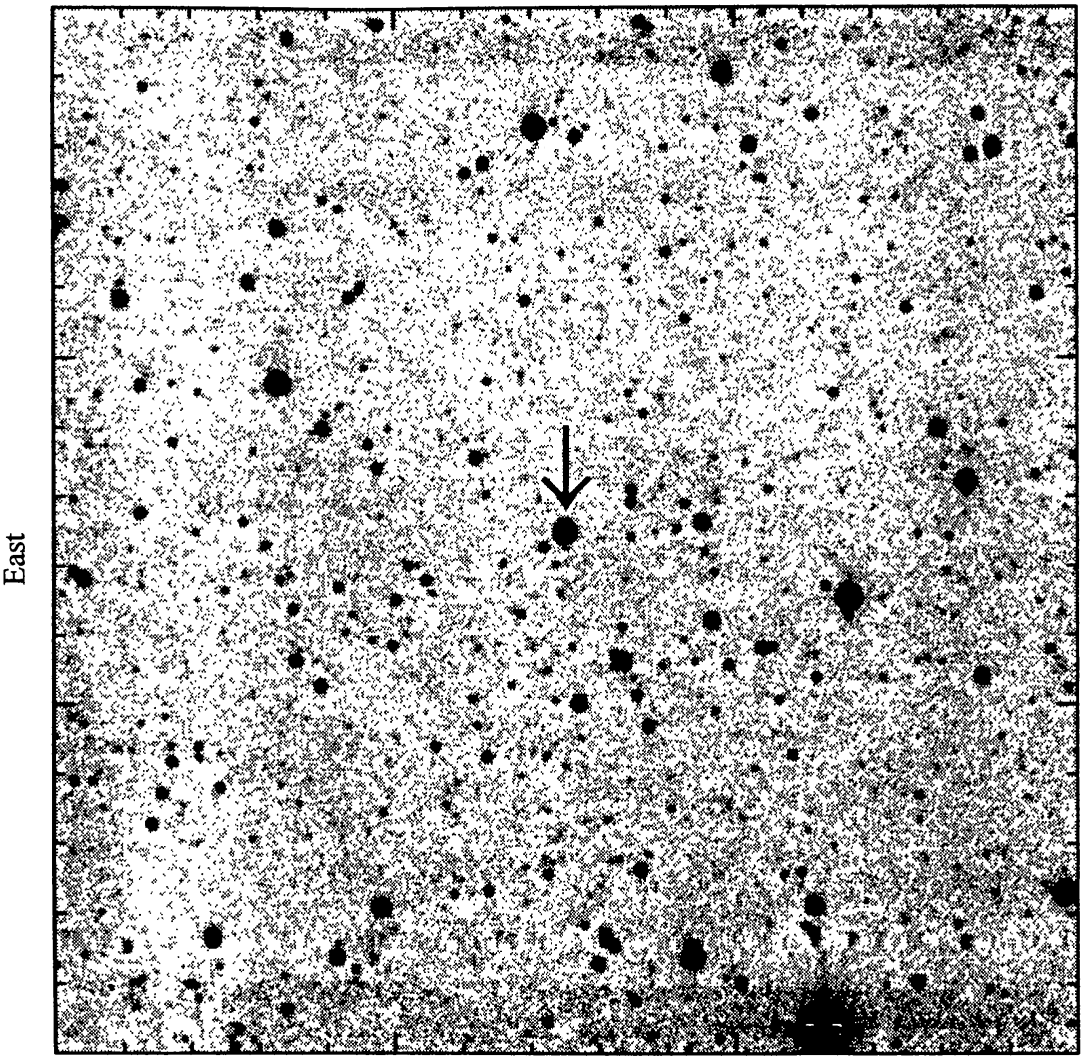

Bottom: The same region of the sky as shown in Figure 1, taken with the CTIO 0.9-meter telescope, August 20, 1994. Similar filters were used for both observations. The image is negative, so the stars appear as dark spots. The optical counterpart of GRO J1655-40 is marked with the arrow.

0.9 times the speed of light. The geometry of the system and relativistic effects can make these jets to appear move faster than the speed of light, hence the term "superluminal jets." Superluminal jets are sometimes seen in extragalactic quasars and in active galactic nuclei. GRO J1655-40 is only the third galactic source to have relativistic jets and only the second source to show apparent superluminal motion (Hjellming and Rupen 1995). The other galactic source showing superluminal motion is behind at least 20 magnitudes of optical extinction (Mirabel and Rodriguez 1994), so much less is known about that system. Since GRO J1655-40 is compact and nearby, it evolves quickly and it can be imaged with high resolution. These two properties and others make GRO J1655-40 an extremely important source for the study of relativistic radio jets (see Hjellming and Rupin 1995).

GRO J1655-40 was considered to be a "black hole candidate" based on its X-ray properties during the initial outburst. That is, certain X-ray characteristics of GRO J1655-40 were similar to the X-ray outburst characteristics of other dynamically confirmed black hole systems. Recently, Bailyn *et al.* (1995b) obtained extensive photometry of GRO J1655-40 when the source was near quiescence. They also obtained high quality spectra of the source. They established the orbital parameters of the system, and hence constraints on the mass of the primary. Bailyn *et al.* (1995b) showed that the minimum mass of the compact object in GRO J1655-40 was in excess of 3.1 solar masses. This lower limit on the mass is more than the mass of a stable neutron star, thereby implying that the compact object is a black hole. The photometric time series obtained by Bailyn *et al.* (1995b) clearly shows the existence of eclipses (confirming earlier suspicions that GRO J1655-40 may be eclipsing [Bailyn *et al.* 1995a, Hjellming and Rupin 1995]), making GRO J1655-40 the first known eclipsing X-ray nova. The existence of eclipses puts severe constraints on the inclination of the orbital plane to the line of sight (we must be looking at the orbit nearly edge-on to view eclipses). The biggest uncertainty in obtaining the exact mass of the primary (rather than just a lower limit on the mass) is the inclination, and this uncertainty is effectively removed in the case of GRO J1655-40.

5. Conclusion

At V=17 in quiescence, GRO J1655-40 is the brightest known black hole X-ray nova. Thus we expect to be able to study it in detail never before possible with the other known black hole systems. This exciting system also provides us with the unique opportunity to study many interesting astrophysical processes such as jet formation and accretion onto compact objects. Hopefully we can learn much more in the coming months and years as we further study this unique object.

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