Lecture 4A : Hearts of Darkness

4.1 CASE STUDY : A NEW X-RAY SOURCE

The BATSE the (Burst and Transient Source Experiment) was a very succesful NASA high energy experiment aboard the Compton Gamma-Ray Observatory mission, launched in 1991 and running for 9 years. In this lecture we are going to follow a particular source of X-rays picked up by the satellite in one of its sky surveys.

The source we'll study is "GRO-J1655−40", discovered as a bright burst of X-rays seen by BATSE on July 27th, 1994. For a while it was the brightest X-ray source on the sky. The source's name includes its approximate position on the sky, at $\alpha = 16^h55^m$ and $\delta = -40°$.

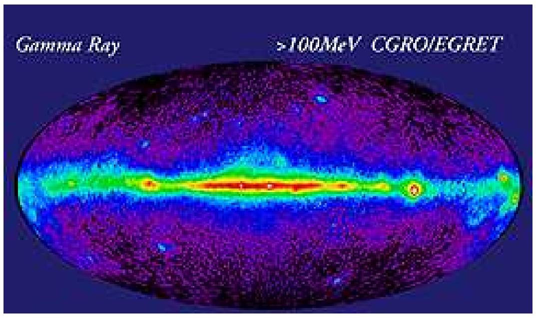

Figure 4.1. All sky distribution in Galactic coordiantes of gamma ray flux, obtained with the EGRET instrument on the CGRO mission. The Galactic plane is a major source of gamma radiation.

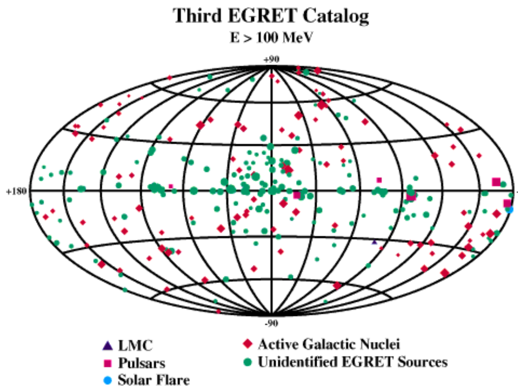

Figure 4.2. Map of some point sources on the gamma-ray sky, in Galactic coordinates. Point sources with significant flux above 100 MeV are indicated by with color-coded symbols. They are mainly active galaxies and pulsars where identified; there are many as yet unidentified sources. The EGRET instrument identified over 60 galaxies of a new type, characterized by extremely variable gamma-ray emission, and emitting mainly in gamma-rays. Source : http://cossc.gsfc.nasa.gov/cgro/egret_src.html.

4.2 WHAT IS THE NEW SOURCE?

X-rays are known to come from supernova remnants, pulsars, active galaxies, quasars, massive galaxies, galaxy clusters, neutron stars and black holes. We want to decide between these or other possibilities.

First fact: the source is at $\alpha = 16^h55^m$ and $\delta = -40°$. This is directly in the Galactic plane, and has Galactic coordinates $(l, b) = (345°, 5°)$. Figure 4.1 shows the high energy gamma ray map in Galactic coordinates from the EGRET instrument on the mission. The Galactic plane is a major source of gamma radiation. Individual sources of gamma rays, whith some identifications, have been shown in figure 4.2. The situation is much less clear for X-rays (figure 4.5); in this region, the Galactic plane is indistinct and the sources of radiation are dominated by bright point like sources.

GRO-J1655−40 is right in the Galactic plane, which strongly suggests that the source is in the Milky Way. This suggests a neutron star, supernova remnant (SNR) or black hole candidates.

The satellite continues to check back on the source every few days (see figure 4.4); meanwhile, radio maps are obtained of the region on the sky around the source, at the Very Large Array (in New Mexico) at 1.49 GHz and at Molonglo in Australia at 0.843 GHz. In the meantime, attempts are underway to find the source in the optical. The UK-Schmidt all sky survey is the appropriate one to use, because the GRO-J1655−40 is well into the southern hemisphere; this survey consists of several thousand 30×30 cm glass plate images of the sky, to about visual magnitude 20, covering about 5×5 degrees each. The accuracy of the coordinates are not good, due to the low resolution of the X-ray instrument of about 0.3 degrees. At CITO (Cerro Tololo Inter-American Obervatory), the 0.9 meter telescope is used to obtain 15 CCD images of a region 0.6×0.6 degrees around the source. If the source turns out to be unresolved in the optical (i.e. it is not an extended source, like a galaxy), then it will only be about 1 arcsecond in size and quite difficult to identify amongst many thousands of similar looking objects on the images. Monitoring the field over several nights is the key, because it is likely to be highly variable.

August 10th, 1994: one particular object is identified in the field – it varies by up to half a magnitude irregularly. We now have a possible source in the optical, at $\alpha = 165400$, $\delta = -395045(2000)$. It's in the middle of figure **??**, which is 15 minutes on each side.

Having gotten a target object, a spectrum can be obtained. Figure **??** shows a spectrum in the optical, obtained August 12th 1994 at the 1.5 meter telescope at the European Southern Observatory at La Silla in Chile. The spectrum shows a variety of **emission lines** on a blue continuum,

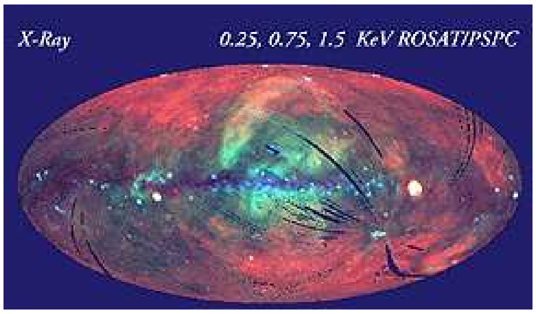

Figure 4.3. All sky distribution in Galactic coordiantes of X-ray flux, from the ROSAT mission. The Galactic plane is much less distinct in this image than it is in gamma-rays. The X-rays are mainly due to supernova remnants (some of the arclike features) as well as individual sources of X-radiation from close binary stars or black hole candidates. Bright X-ray sources can be divided into two groups: those within the Galaxy and this without. Galactic sources tend to lie in the Galactic plane and toward the Galactic center. Far above the Galactic plane, one sees predominantly extra-Galactic sources, such as the nearby galaxies LMC and Andromeda. Some of these sources are brighter in X-rays than the total luminosity of the Sun. Source : http://www.xray.mpe.mpg.de/rosat/survey/sxrb/12/ass.html

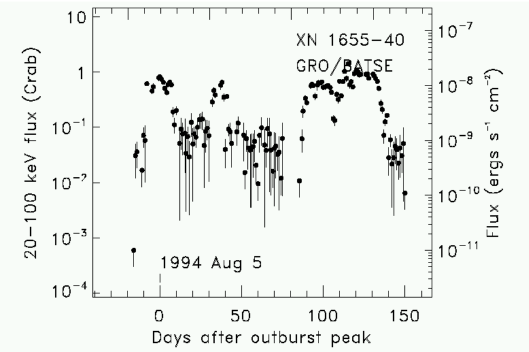

Figure 4.4. Xray-lightcurve for GRO 1655−40 for a few hundred days after discovery, showing that the source is highly variable. The flux is in units of the luminosity of the Crab nebula. Source : astro-ph/9707138

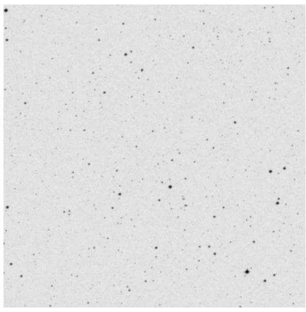

Figure 4.5. SERC sky survey image of the field around GRO-J1655−40. The source is at field center, but is difficult indeed to make out from the many surrounding sources. The image is in the optical region. Source: Space Telescope Science Institute (STScI)

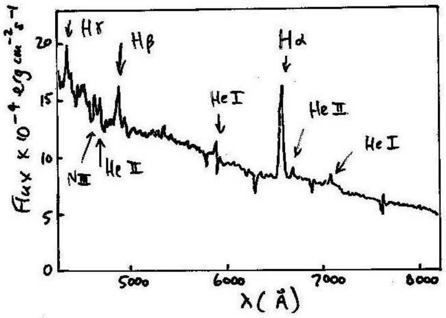

Figure 4.6. Spectrum of GRO-J1655−40 in the optical, obtained August 12th 1994 at the 1.5 meter telescope at the European Southern Observatory at La Silla in Chile. The source is characterised by many emission lines on a blue continuum, and is typical of X-ray binaries. Source: Bailyn et al, 1994)

lines due mainly to hydrogen and Helium. The spectrum is typical of so-called X-ray novae in outburst. The source appears to be a new **X-ray binary** star, consisting of a neutron star (or black hole), girthed by an **accretion disk**, and accompanied by a low mass, main sequence star.

X-ray binaries are formed from normal binary stars, one of which has left the main sequence. Two main pathways exist, as illustrated in figure 4.7.

In the radio region, a study is undertaken at the VLA, monitoring the sytsem regularly during August and September 1994. First observations show an **unresolved** source, less than 100 milliarcsec (mas) in angular size. Six days later, the radio flux peaks and the source is now about 200 mas, extending roughly East-West. After this, a "jet" and series of "blobs" appear. Optical identification of the secondary star (see below) indicates that the system is about 4 kpc away. The speed of these blobs away from the central source can then be computed and turns out to be super-luminal (apparently faster than the speed of light), indicating that one of the jets is pointed toward us as observers. Apparently superluminal motion can result in this case, even if the motion is actually subluminal. The blobs appear on time scales of a few days (figures 4.8, 4.9).

Radio observations at 5 different wavelengths (1.49, 4.9, 8.4, 14.9 and 22.5 GHz) show a **power-law spectrum** with an index of $\alpha \approx -0.6$. This is a classical indicator of synchrotron emission, implying relativistic electrons moving in a magnetic field.

The system was monitored in various bands for months afterwards — in the optical it eventually dropped enormously in brightness (Feb-Mar 1996), and became relatively constant in magnitude, a phase referred to as **quiescence**, meaning 'quietness'. This is an opportunity to study the system without the complications of high energy and other emissions due to the accretion disk and possible jets (as we'll see later).

A study in the optical is undertaken with the 1.5 meter and 4.0 meter telescopes at CTIO in Chile, which identifies the MS companion to the compact object as a F type giant star, and its orbital motion is measured in detail (figure 4.10). The amplitude of the radial velocity is large, and the period is rather small (2.62 days).

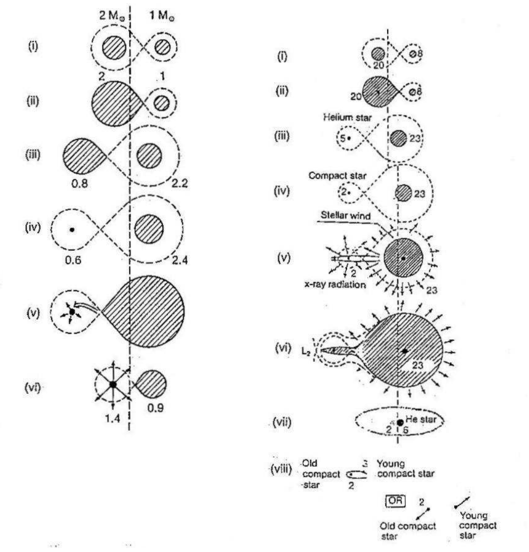

Figure 4.7. Two main pathways for stellar evolution in binary systems. On the left, evolutionary scenario for low mass stars: (i) both stars on the main sequence (MS); the roche lobes of the stars are indicated by dashed lines, showing the point at which the gravitational attraction toward each of the two stars is in balance (ii) the more massive star has begun to evolve, filling its roche-lobe; mass transfer takes place to the lighter star; the masses in each star are indicated going down the plot (iii) a light sub-giant has formed from the initially more massive star, and the MS star is now considerably heavier than it was (iv) a white dwarf (WD) has formed from the sub-giant (v) the MS star begins its own evolution up the giant branch, earlier than it would otherwise have done where it a single star; mass begins to be transferred to the WD, and the object becomes a strong X-ray source(vi) sufficient matter has accreted onto the WD, exceeding the Chandrasekhar limit, and it explodes as a type I supernovae. Right: evolutionary scenario for massive stars (i) both stars are in the MS phase (ii) the higher mass MS star has begun to evolve and transfer mass to the companion (iii) the helium core of the initially more massive star is revealed, leading to (iv) the supernova explosion of this star, to become a neutron star or black hole, often referred to as a'compact object' (v) the initially lighter MS star now goes to the giant branch, and develops a stellar wind (vi) matter transfer to the compact object begins, with the development of an accretion disk; the source is now a strong X-ray emitter (vii) the giant star has lost its outer layers, exposing the Helium core (viii) this core eventually explodes as a supernova, leaving a binary neutron star (NS) or black hole system (NS-BH). The explosion may be sufficient to unbind the stars. Source: Fundamental Astronomy, Karttunen et.al. 1987).

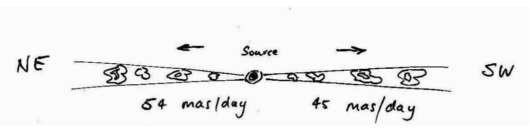

Figure 4.8. Schematic diagram of the radio emitting blobs emerging to the NE and SW. The North-East blobs have mean motions of 54 mas/day, and are probably superluminal. This is probably the jet which is pointed toward us. The receeding jet has blob motions of 45 mas/day and is directed to the South-East

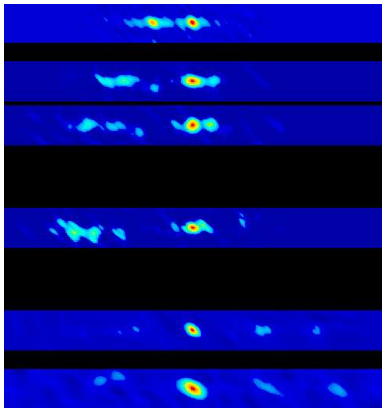

Figure 4.9. Radio maps, made with the VLBA, of the blobs of material emerging from the central bright source in GRO 1655−40. The dates of observation (going from top to bottom) are 18-19 Aug, 22-23 Aug, 25-26 Aug, 1-2 Sep and 8-9 Sep 1994. The sequence has been laid out so that the vertical axis is a linear sequence in time. The horizontal scale is approximately 3 arcseconds across, and the central source has been used to align the maps. Several of the blobs can be followed moving outward from the central source. The motion to one side is 54 mas/day, and to the other 45 mas/day (see also figure 4.8). Image courtesy of NRAO/AUI.

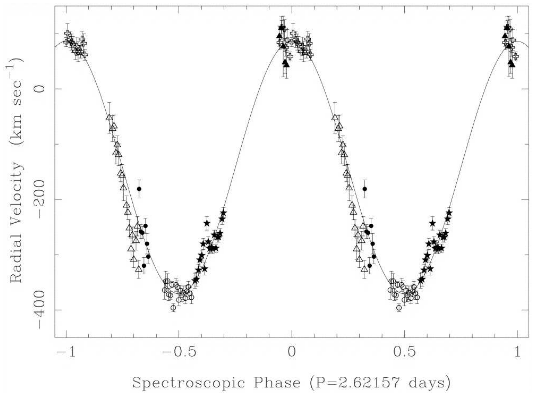

Figure 4.10. Radial velocity curve for GRO 1655−40. A sin curve fit is shown, based on the model presented by Orosz and Bailyn (discussed in the text). The curve is plotted as a function of spectroscopic phase, for a period of 2.62157 days.

The radial velocity can be quite well fit with a sin curve, with an amplitude of 456 km/s and a period of 2.62 days. The visible star of the system, the F subgiant, has a mass of about 2.3 $M_{\odot}$, meaning that the mass of the compact object can be computed as about 7.0 $M_{\odot}$. As far as we know, no object can be this massive and still in stellar form (the limit is about 1.4 $M_{\odot}$ for neutron stars and white dwarfs); the conclusion is that this is a black hole. Its high mass, and the very detailed observations possible with this system make it one of the best black hole candidates.

The optical light curve is very regular, showing two dips of unequal depth — the classic signature of some sort of eclipsing system (figure 4.11). Armed with these data, Orosz

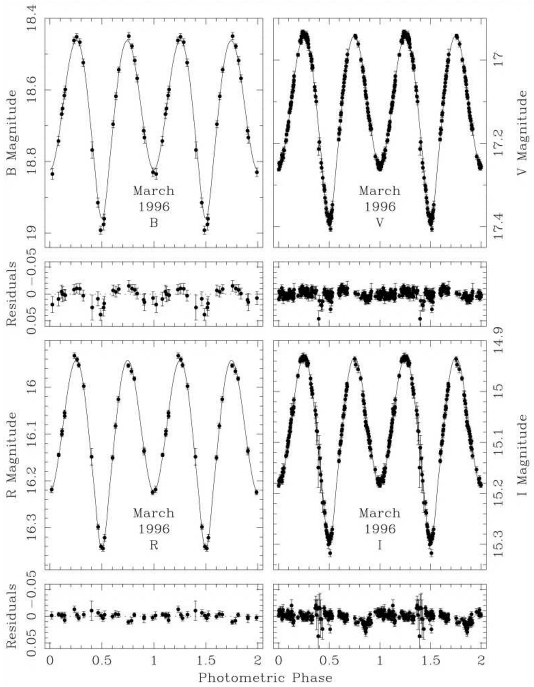

Figure 4.11. Apparent luminosity of GRO 1655−40 in B, V, R and I bands, as a function of prbital phase. Model fits are shown by the solid lines, and the residuals to the fits in the smaller panels.

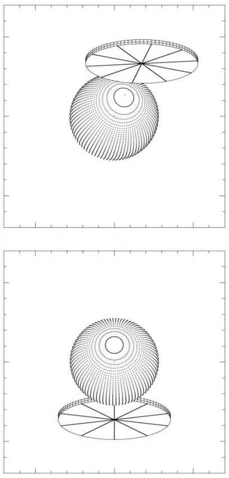

Figure 4.12. Model of the system, shown at phase angles 170° (upper panel) and 0° (lower panel). The star and disk alternatively eclipse each other partially.

and Bailyn (1996) have constructed a model for the system, illustrated by figure 4.12.

The model consists of a central black hole, with a mass of $7.0 \pm 0.2M|odot$, around which is a fairly thin accretion disk and a subgiant secondary (F IV) star (2.3 $M_\odot$). The rotation axis of the system is tilted by about 30 degrees to the line-of-sight. Emiision from the system in the optical is primarily due to black-body radiation from the secondary ($T_{\rm eff} \approx 6500$ K) and the accretion disk, which has a temperature at the outer rim of about 4400 K, increasing inward to temperatures at which X-rays are being produced (several keV). Full details of the best fitting parameters of the model are shown in figure 4.13.

Table 4.1. Fitted parameters to the model for GRO 1655−40, as illustrated in figure 4.13

Parameter	symbol	value
inclination to line-of-sight	i	$\approx 70°$
primary mass	M_1	$\approx 7M_\odot$
secondary mass	M_2	$\approx 2.3M_\odot$
mass ratio ass	Q	≈ 3
accretion disk radius	r_d	≈ 0.75*
temperature, disk rim	$T_{\rm disk}$	≈ 4400 K
flare angle of disk	β	$\approx 2.2°$
temperature of secondary	$T_{\rm eff}$	≈ 6500 K
power law exponent of disk	ξ	≈ -0.2

* relative to radius of the Roche-lobe.
Source: Orosz and Bailyn, 1996.

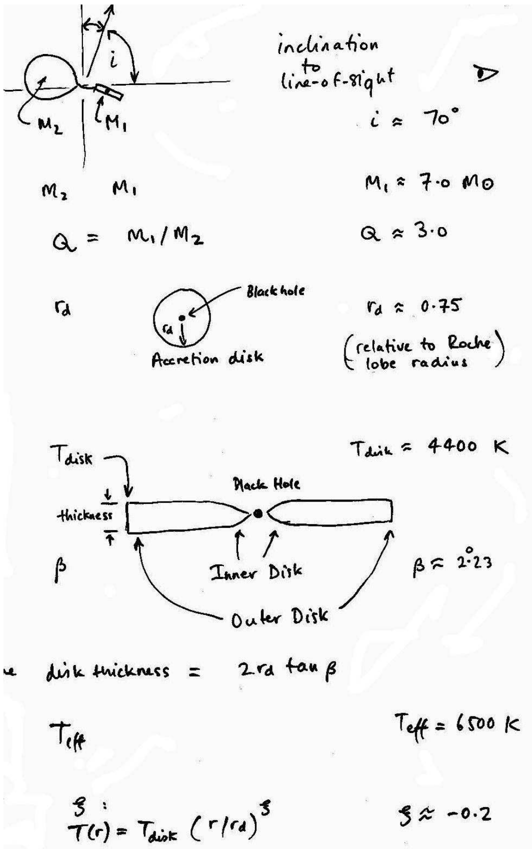

Figure 4.13. Model parameters of the Orosz and Bailyn model for GRO 1655−40. Best fitting values are shown in table 4.1.

Figure 4.12 is shown to scale — i.e. the star and accretion disk are in close proximity and of similar physical size. Once per orbit, the star partially eclipses the disk, and vice-versa. Only a small part of either body is eclipsed, so that the dips light curves are relatively small. It is the cool rim of the disk which is being eclipsed by a hotter star, so that the

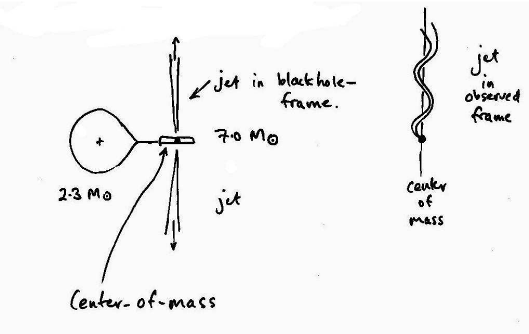

Figure 4.14. Schematic of jet, disk and companion, showing how, in the frame of the observer, blobby structure in the jet could be related to the period of the system.

light curves are quite colour dependent (figure 4.11) — note how well the model fits the data well in all of the observed colour bands B, V, R and I. The model is a very good fit to these data.

What about those blobby radio jets? The blobs were appearing and then moving away from the central source every few days — quite similar to the orbital period of the system (2.26 days). Could these be related? Figure 4.14 shows that, since the black hole mass and companion mass are not so different, the centre-of-mass of the system is offset a little from the black hole (which is presumably at the jet base). This is a simple way to produce a corellation with the system period, but at present the evidence to support this idea is weak.

Systems like GRO 1655−40 have become known as microquasars — and very useful probes for the study of quasars, which also are thought to contain a central compact object, accretion disk and jets. The much lower mass of the central object (few $M_\odot$, compared to $10^4 - 10^{10} M_\odot$ for quasars) lends the very great advantage that these sources operate on much shorter timescales than quasars proper. One can follow their goings-on much more easily!

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GRO (Compton Gamma-Ray Observatory) http://cossc.gsfc.nasa.gov/

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