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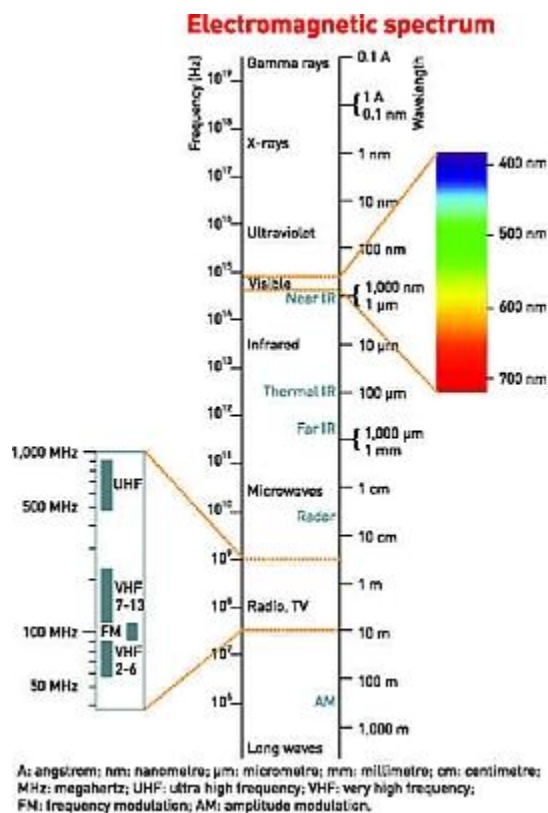
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SPACE

Cosmic crash

R. RAMACHANDRAN

Evidence of a gamma-ray burst picked up by a NASA spacecraft has scientists wondering what mighty cosmic event could have caused it.



A COSMIC explosion that occurred about four billion years ago, just when the earth was being born, has scientists wondering what it could be. The electromagnetic flash from that was picked up by the Burst Alert Telescope (BAT) of the National Aeronautics and Space Administration's (NASA) Swift Gamma Burst Mission spacecraft on March 28. Preliminary analyses of the unusual characteristics of the spectral distribution of the emission, which are still ongoing nearly three months after the first signal was picked up, have led two groups of scientists who observed

it to believe that it could be because of a super massive black hole (SMBH) more than a million times the mass of the sun literally ripping apart a star of about the sun's mass and slowly gobbling it up, resulting in perhaps the biggest and the brightest explosion seen yet from the earth. What makes it particularly unusual is that it is an extremely rare event in which the earth happened to be right in the direction of the jet-like emission from it.

Given the importance of the observation, the two groups wrote up their respective papers and submitted them for publication in three weeks' time. They were published in the June 17 issue of the journal Science as companion research articles. One group was headed by Joshua S. Bloom of the University of California, Berkeley, and the other by Andrew Levan of the University of Warwick. A few names, including those of the two lead authors, figure in both the groups. "Despite the power of the cataclysmic event, we still only happen to see this event because our solar system happened to be looking right down the barrel of this jet of energy," Levan remarked in a press release from Warwick.

The spacecraft Swift is a multi-wavelength space observatory dedicated to the study of gamma-ray burst (GRB) science. Its three instruments – the BAT, the X-ray Telescope (XRT) and the UV/Optical Telescope (UVOT) – work together to observe GRBs, the most powerful explosions that the universe has seen since the Big Bang. They occur approximately once a day and are brief (a few milliseconds to a few hundred seconds) but emit flashes of intense gamma rays. Scientists do not yet know exactly what causes them, but these are believed either to result from the massive stellar explosion (supernova) caused by the collapse of a star to form a neutron star or a black hole or to be the product of the collision of two neutron stars.

MARK A GARLICK



AN ARTIST'S REPRESENTATION of what scientists think the star may have looked like at the start of the disruption by a black hole at the centre of a galaxy 3.8 billion light years away which resulted in the outburst now known as Sw 1644+57.

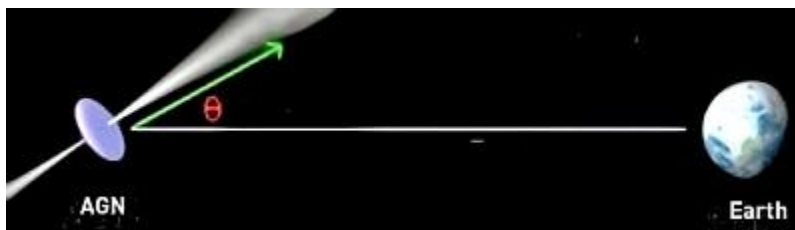
The largest instrument on board Swift is the BAT, which can view approximately one-sixth of the entire sky at one time. It is designed to detect 100 or more GRBs a year. Within seconds of the BAT picking up a GRB, the spacecraft automatically orients the XRT and the UVOT to determine the spectra of the "afterglow" from the event in the X-ray, ultraviolet (UV) and optical wavelengths with high precision.

When Swift first detected a series of powerful X-ray/gamma-ray flashes from an uncatalogued galaxy within the constellation Draco, astronomers thought that it was a GRB from a star collapse and called it GRB 110328A (the number representing an event of March 28, 2011). However, astronomers observing this “GRB” soon realised that it was no ordinary one as the maximum brightness from the event was nearly a trillion times that of the sun. Therefore, on March 31, Bloom sent out an e-mail circular (GCN 11847) on the GRB Coordinates Network (GCN) suggesting that it was not a typical GRB but a high-energy jet produced by “the result of a tidal disruption event [TDE]” of a sun-sized star by a black hole a million times more massive, which was being “viewed (nearly) face on to a newly formed jet”.

“With this interpretation,” Bloom and colleagues wrote, “we would expect the emission to be astrometrically coincident with the nucleus of the host galaxy (something not observed with GRBs in general), exhibit time-variable behaviour at radio wavebands... and a rising optical/IR event over the next few weeks...” The explosion was owing to a star getting literally torn apart because it had wandered away from its stable orbit around the centre of the galaxy and got too close to the black hole perhaps because of some cosmic accident. Such an accident could have been a close encounter of the star with another star or a dense gas cloud. It also could be that the star started out close and after millions of years its orbit brought it closer and closer to the centre of the galaxy.

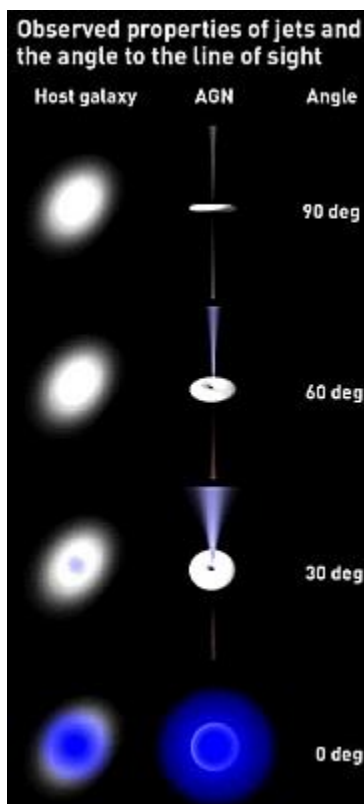


WHAT THEY THINK of the aftermath of the event, which blasted jets of energy from the black hole, one of which pointed directly at the earth's galaxy.



VIEWING ANGLE (Θ), and (below) a classification of active galactic nuclei (AGN). At 90°

to the jet: radio galaxy/Seyfert 2 galaxy; 60° & 30° to the jet: quasar/Seyfert 1 galaxy; and 0° to the jet: blazar.



The e-mail immediately set off a flurry of activity in astronomy groups around the world. The supplementing observations by other space observatories – such as the Hubble Space Telescope, which has been taking extraordinary high-resolution images of the universe in optical, UV and the near-infrared (IR) for nearly two decades; the Chandra Observatory, launched in 1999 and designed to observe X-rays from high-energy regions of the universe; the Fermi Gamma-ray Space Telescope, launched three years ago; and the XMM-Newton, which is another orbiting X-ray mission, launched by the European Space Agency (ESA) in 1999 – became critical to determine the precise location of the event and enable a plausible explanation for it.

Astronomers quickly noticed that there was a small, distant galaxy very near the Swift position. A deep image taken by Hubble on April 4 pinpointed the source at the centre of this galaxy, which lies 3.8 billion light years away. The distance is inferred from the measured high red shift (stretching of emitted radiation to longer wavelengths because of the expansion of the universe) of 0.3534, and Hubble's Law tells us that red shift is proportional to the distance of the emitting galaxy.

The same day, astronomers made a four-hour-long exposure of the intriguing source with the Chandra X-ray Observatory, which can locate a source 10 times more precisely than Swift. This showed that the source lay at the centre of the galaxy that Hubble had imaged. These observations thus confirmed Bloom's initial insight, and the event was rechristened in the papers as Sw 1644+57. “This is truly different from any explosive event we have seen before,” Bloom

said in the Berkeley press release. What made this event (Sw 1644+57/GRB 110328A) stand out from a typical GRB were its duration, which was longer than any GRB on record; its brightness, which was 100 times higher than so-called active galactic nuclei (AGN); and the fact that it appeared to come from the centre of a distant galaxy. Typical GRBs are associated with regions of recent star formation, but star formation at the centre of a galaxy is rare, points out Dipankar Bhattacharya of the Inter-University Centre for Astronomy and Astrophysics (IUCAA) in Pune.

According to the accompanying Science paper of Levan and colleagues, “Unlike any normal long-GRB [lasting a few minutes], the source remained bright in the X-rays [afterglow] for more than two weeks.” Levan and co. estimate that the total energy output in the first million seconds (about two weeks) after the outburst was about 10 per cent of the energy of the sun. “While these numbers are not abnormal for long-duration GRBs,” says their paper, “the properties of this outburst are clearly distinct from the long-duration population.”

Most, if not all, galaxies, including the Milky Way, are believed to harbour massive black holes (MBHs) at the centre, which are a million or even a billion times the mass of the sun. One would naturally imagine that these MBHs or SMBHs would be constantly swallowing matter because of their extremely strong gravitational force. However, most of them are quiescent or dormant without matter falling into them. But if a black hole encounters a gas cloud, a disk called an “accretion disk” forms around it. This accreting matter gains a lot of energy as it falls into the gravity of the black hole, and the disk heats up. As a result, a huge amount of radiation is emitted. In about 10 per cent of galaxies, the SMBHs at the galactic centres seem to be active because of the continuous feeding of gaseous matter and ferociously consuming gas around them. Such galaxies are called AGNs, or quasars.

Ironically, such active black holes, which may be billions of light years away, are easy to detect because of the strong emission from the swirling gases around them even though the black holes themselves do not emit any light. In fact, these are some of the brightest objects in the universe. Many of them emit high-energy X-rays and some of them gamma-rays as well. But, as mentioned above, such X-ray or gamma-ray emissions from AGNs are much less strong than what was detected by Swift in Sw 1644+57.

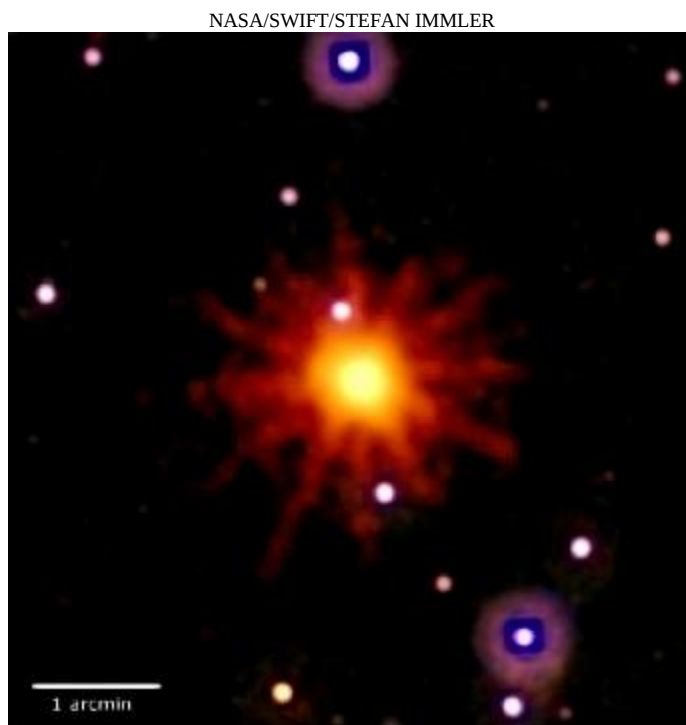
Further, as Bloom and co. have pointed out in their paper, “While variability is common to all AGN – fundamentally tied to the unsteady accretion of flow of gas towards the central MBH – the timescale for active MBHs to dramatically change accretion rates (leading the source to, for example, ‘turn off’), is much longer than a human lifetime.... This rapid increase in accretion rate cannot result from gas entering the sphere of influence of the MBH, because this would require a timescale [of more than] 10,000 years....” That Sw 1644+57 was indeed quiescent for long was confirmed from the data of the Fermi satellite's Large Area Telescope (LAT).

In the circular GCN 11862, Nicola Omodei of Stanford University and others reported that in the 27 months of LAT observations no significant gamma emission was seen from the direction of GRB 110328/Sw 1644+57. “Knowing that this object could be highly variable, we investigated possible emissions on timescales of 5 and 2 days over the lifetime of the Fermi mission. No significant emission was seen in any of the time bins in the light curve,” reported the circular. The accompanying paper of Levan and colleagues says that re-examination of previous gamma-

ray observations of this region suggests that the source was at best present a few days before the initial trigger (on March 28) but not earlier.

So what Swift observed was a one-off event. This long-duration gamma-ray flare, therefore, could conceivably be the emission from the relatively slow disruption of a star that has trespassed closer than the “disruption radius” of an otherwise quiescent SMBH and then was accreted by it. Bloom has explained: “As the black hole rips the star apart, the mass swirls around like water going down a drain, and this swirling process releases a lot of energy.”

Bloom and colleagues estimate in their Science paper that some 10 per cent of the infalling star's mass is turned into energy and irradiated as X-rays from the swirling disk or as X-rays and higher energy gamma-rays from a relativistic jet that punches out along the rotation axis. The earth happened to be just in the eye of the gamma-ray beam. Thus, they argue that a TDE provides a natural explanation for Sw 1644+57. What is a TDE and how does this ripping apart of a star actually happen? The gravitational attraction of a black hole is extremely strong. But it gets weaker with distance.



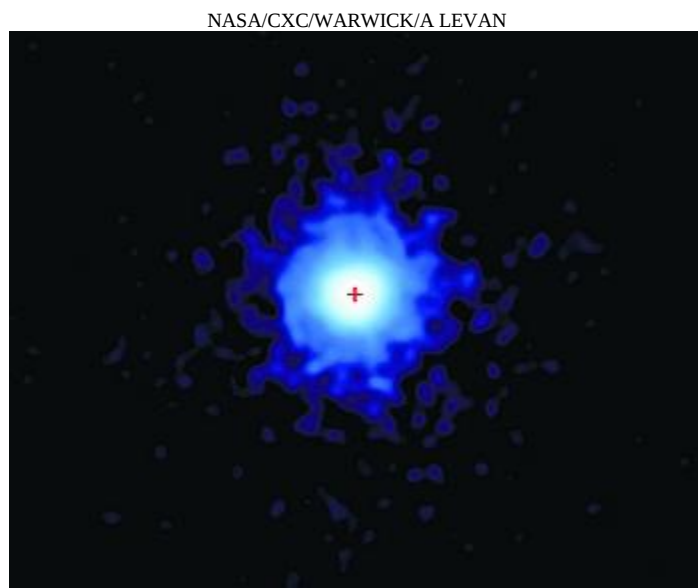
IMAGES FROM SWIFT'S Ultraviolet/Optical (white, purple) and X-ray telescopes (yellow and red) were combined in this view of GRB 110328A. The blast was originally detected only in X-rays/gamma rays, which were collected over a three-hour to four-hour period on March 28.

Stars are big objects that are a million or more kilometres across. That means when a star is in the proximity of a black hole, one side of the star will be substantially closer to the black hole than the other so that the near side feels a stronger gravity than the far side. This has the effect of stretching the star in much the same way that the differential gravity due to the moon between the two sides of the earth causes ocean tides on the earth. A star, of course, is held together by its

own gravity. Since the stretching effect or the tidal force due to the black hole becomes stronger and stronger as the star gets closer and closer, at some point it overcomes the internal gravity and literally tears the star apart.

Of course, this is not the first ever such event. According to Bloom, there have been some indications that TDEs have been seen before in UV, X-ray and visible light but never before at gamma-ray energies. Also, none has shown the brightness of the X-ray afterglow or variability seen here. The source repeatedly flared and since April 3 apparently brightened more than five times. According to Levan, who also led the Chandra observations, the textbook example of a TDE usually only creates a faint burst of radiation. “But Sw 1644+57,” he said, “was full of gamma-rays that ranged somewhere between 1,000 and 10,000 times brighter than the events that we’ve seen before.”

“We think,” Bloom has said, “the event was detected around the time it was as bright as it ever will be, and if it’s really a star being ripped apart by an MBH, we predict that it will never happen again in this galaxy.” Bloom said in an e-mail: “There are probably 3-6 reasonably strong examples of such events over the past decade. However, this is the first time that the jet was pointing at us. It’s a special vista on that rare event.”



NASA'S CHANDRA X-RAY Observatory completed this four-hour exposure of GRB 110328A on April 4. The centre of the X-ray source corresponds to the very centre of the host galaxy (red cross) imaged by the Hubble Space Telescope.

“The X-rays and gamma rays,” Levan said in an e-mail response, “were concentrated into a jet of light that we see beamed at us. If we hadn’t been viewing down the axis of this jet, we wouldn’t have seen an event like this.”

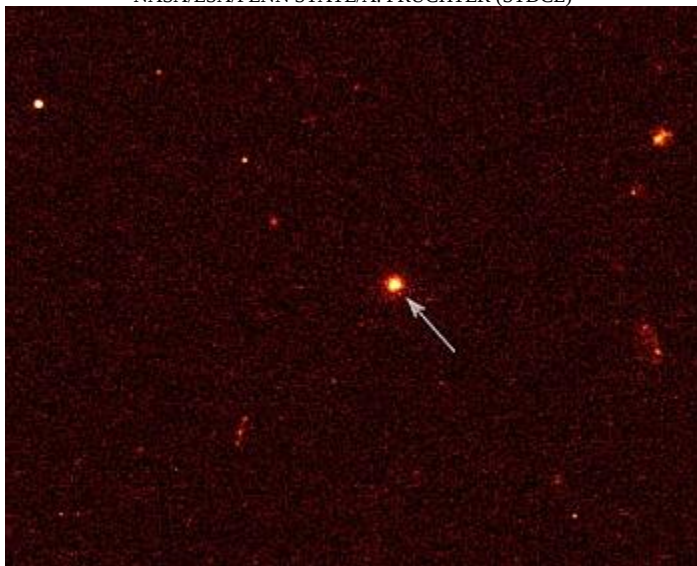
Scientists believe that these X-rays may be coming from the matter moving near the speed of light in a particle jet that forms as the star’s gas falls toward the spinning black hole. When emission moving close to the speed of light is viewed nearly head on, a phenomenon called

relativistic beaming (also called headlight effect), which is akin to relativistic Doppler effect, occurs, causing the brightness or luminosity of the radiation to increase. Such random events, especially looking down the barrel of a jet, according to scientists, are incredibly rare, probably once in 100 million or a billion years in a galaxy. But, given that Swift detected only one such event in about six years of monitoring, the “all sky rate” of TDEs accompanied by relativistic ejecta, instead of that in an individual galaxy, is at least 10 a year out to a similar distance.

Although the event Sw 1644+57 is, as discussed above, quite distinct from an AGN, Bloom and co. have tried to give an analogy with a subclass of AGNs, called blazars from the general geometry of the event as well as the underlying physical mechanisms for the emission in the different wavelengths. Blazars are the most variable of AGNs, whose emissions too include a relativistic jet that is pointing in the direction of the earth, and it is generally observed “down” the jet, or nearly so.

The black holes involved in blazars typically have masses of 100 million to a billion times that of the sun and are optically and radio bright. In blazars, Bloom and co. point out, “the high-energy emission is believed to be caused by inverse Compton (IC)”. According to their paper, the energy distribution of Sw 1644+57 has two peaks, at far IR and at X-ray/gamma-ray wavebands, which they say cannot be accounted for by the thermal emission from the disk or the accretion-powered outflows. “Instead, the overall spectral shape,” says the paper, “is reminiscent of blazars, for which peaks at low and high energies are modelled as synchrotron and inverse Compton (IC) emission, respectively.”

NASA/ESA/PENN STATE/A. FRUCHTER (STDCL)



A VISIBLE-LIGHT IMAGE of GRB 110328A's host galaxy (arrow) taken on April 4 by Hubble's Wide Field Camera (WFC3).

The former is caused by the emission of electromagnetic radiation due to the acceleration of relativistic electrons in the magnetic field of the accreting matter and the latter due to the scattering of photons (accretion disk photons, photons from within the jet itself, and photons from structures external to the accretion disk) by matter that causes the frequency of photons to increase (upscattering) – as against Compton scattering where frequency decreases. “This

model...appears to best accommodate the data and predicts the long-term evolution of the radio and infrared transient [in the source Sw 1644+57],” says the paper.

It may be mentioned here that radio astronomy groups, including the one from the Tata Institute of Fundamental Research (TIFR), that use the Giant Metrewave Radio Telescope (GMRT) near Pune, observed the source from its radio emission at a position consistent with the other measurements of Sw 1644+57. However, as would normally be expected from TDEs, the astronomers have not seen rising UV-optical emission nor slowly evolving thermal X-ray emission as yet. This, it is argued, could be due to the suppression of UV by the dust and outshining of the X-rays by the much brighter jetted emission.

Assuming that correctness of the existing models of TDEs, Bloom and co. believe that the thermal X-ray emission may emerge in the scale of months. “If the tidal disruption flare hypothesis is correct,” their paper says, “Sw 1644+57 will fade over the coming year and will not repeat.” However, Levan, in an e-mail response, said that most of the TDE models that exist do not predict the relativistic jet that was observed in this case. “What we do see is consistent with the expectations (post-facto) of a shredded star.”

Understanding the demographics of the black holes in galactic centres, as a function of cosmic time, is crucial for understanding the growth of the universe, says a report titled “Probing Quiescent Black Holes: Insights from TDEs” produced by a consortium of institutes in 2009. “Detailed observations of TDEs,” the report says, “can provide an independent means of measuring the masses and spins of dormant black holes in distant galaxies.” According to the report, in the case of the most massive black holes (of mass greater than 100 million solar masses), the disruption radius is smaller than the event horizon (for the black hole) and stars are swallowed whole without disruption. In that sense, the observed TDE with Sw 1644 +57 with an MBH of a million solar masses, which is less than the critical mass, has provided astronomers with unique, unexpected and rare insights into the ways in which black holes probably feed and grow. This process of black holes feeding on collapsing stars, scientists believe, has something to do with how galaxies form. According to the report, the rate of TDEs is very sensitive to a galaxy’s nuclear stellar density profile.

The proposed EXIST mission of NASA for conducting a full sky survey for hard X-ray sources had been configured to detect TDEs on the basis of the data provided by the earlier ROSAT and XMM-Newton X-ray missions, which were assumed to be representative of the whole population. However, emissions from Sw 1644+57 imply that there are TDEs beyond current expectations. It displayed such unique characteristics of X-ray and IR emissions that researchers believe they could be witnessing a new class of TDEs.

“These missions don’t exist yet... but it is plausible that they will be optimised to better find this class of events,” said Levan. “While Sw 1644+57 was detected by its gamma-ray emission, it is its behaviour at X-ray and IR wavelengths, lasting at a bright flux level for days to weeks, which most strikingly demonstrates its difference from known classes of high-energy transient. This raises the possibility that similar events which are rather less variable or less luminous could be occurring, but have so far evaded detection by existing satellites,” say Levan and co. in the paper.