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All-sky monitoring of high-energy transients

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Abstract

The use of triangulation, or arrival-time analysis, to monitor the γ-ray sky, is discussed. A network of spacecraft separated by interplanetary distances can monitor the entire sky continuously for γ-ray bursts and similar astrophysical transients. Single experiments in low Earth orbit can also perform this function, and generally have the advantage of greater sensitivity, at the cost of some loss of spatial and temporal coverage.

Introduction

The γ-ray sky is variable on all timescales with which it has been measured so far, from milliseconds to years and longer. Some sources are recurrent, others exhibit both quiescent emission and bursting behavior, and still others manifest themselves in a single outburst. Simply to discover them requires continuous monitoring of the entire sky, and any attempt to understand them benefits from long periods of uninterrupted observations. In principle, this can only be done far from Earth, since low Earth orbiters are subject to Earth occultation and, in most cases, South Atlantic Anomaly interruptions. In practice, though, achieving the best sensitivity means utilizing the largest possible instruments, and virtually all large, single-experiment monitors are in low Earth orbit; conversely, multi-experiment networks, which must be distributed over interplanetary distances, utilize much smaller experiments. In this chapter, we will consider two of the methods which have been in use over the last several decades to monitor the γ-ray sky at energies above roughly 25 keV and over timescales under about 1000 s. Although the techniques can be adapted to sources within the solar system, the discussion will emphasize objects outside it.

Triangulation

In the early days of X-ray astronomy, Giacconi (1972) suggested the use of triangulation to obtain precise locations for cosmic X-ray sources. Although it was to be many years before this technique was used for this purpose, it did come into

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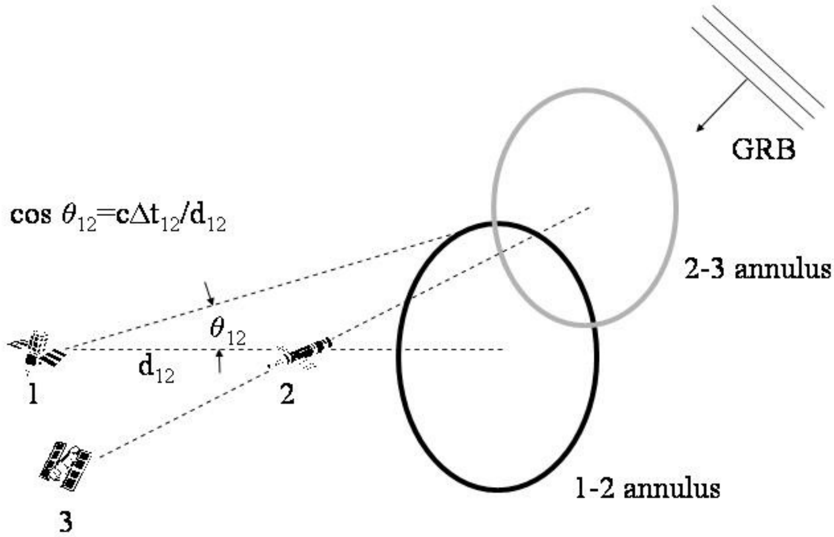

Figure 13.1: The triangulation method. A plane wave resulting from a γ-ray burst is incident on three spacecraft. The difference in arrival times between spacecraft 1 and 2 defines an annulus of possible arrival directions. A third spacecraft gives a second annulus which generally intersects the first one to define two possible arrival directions.

use around the early 1970s for cosmic γ-ray bursts (hereafter GRB), and has been in use almost continually ever since then. Figure 13.1 illustrates the method. A plane wave is incident on three spacecraft. The difference in arrival times between spacecraft 1 and 2, Δt_{12}, and its uncertainty, define an annulus of possible arrival directions by the formula $\cos\theta_{12} = c_0\,\Delta t_{12}/d_{12}$, where c_0 is the speed of light in vacuum and d_{12} is the distance between the spacecraft. (Δt is determined by cross-correlating the light curves recorded on the two spacecraft.) A third spacecraft gives a second annulus which generally intersects the first one to define two possible arrival directions. The third (1–3) annulus intersects the two, but may reduce their areas depending on its associated uncertainty. The ambiguity can be resolved in a number of ways. One is to utilize any inherent directionality in one or more of the individual detectors. Another is by considering whether either of the positions is blocked by a planet, e.g., for an Earth-orbiting or Mars-orbiting spacecraft. A third is to add more spacecraft which are non-co-planar with respect to the first three. The size of the resulting uncertainty box is proportional to the widths of the annuli, which in turn depend mainly on the uncertainty in $\Delta t/(d \sin\theta)$. In practice, the uncertainties in the spacecraft positions are almost always negligible. The plane-wave approximation breaks down for nearby (solar system) objects. When the distances d are in the astronomical unit range, the spacecraft form an interplanetary network, and minute-of-arc accuracy is possible.

Some of the basic principles of the method are the following:

1. The detectors on the various spacecraft do not need to be identical or even similar in area or in type. Good networks have utilized detectors ranging from 20 cm^2 in area to over 100 times this much, and they have utilized materials from inorganic and organic scintillators to germanium. Although dedicated GRB detectors have the advantage of better design, they tend to be more costly; non-dedicated detectors, such as anti-coincidence systems, have the advantage of larger area and higher sensitivity.

2. It helps if the energy ranges of the detectors are similar, but in practice they need only to cover some part of the 25 keV to 100 keV energy range. (The time histories of GRBs are generally different below around 15 keV and above around 100 keV, which makes them difficult to compare.)

3. To achieve accuracies in the minute-of-arc range, the distances between the spacecraft should be in the range of 1 ua and above.

4. The accuracy which can be achieved in cross-correlating two light curves recorded on different spacecraft depends more on the time structure in the light curve than on the number of photons in it. Thus, very short bursts (say 100 ms long) can be localized very accurately, even though the light curves may only contain 50 photons or so.

5. Low Earth orbiting spacecraft will miss at least 30 % of the bursts which they are sensitive to, due to occultation and South Atlantic Anomaly passes. Earth orbiters are an important part of any network, but ideally there should be two or more of them; the current network has four, and a fifth has recently been added.

6. The time resolution of the experiments should be in the 100 ms range or less; the spectral resolution is relatively unimportant.

These constraints place the following requirements on the missions involved.

1. They must have clocks which are accurate to 10 ms or better.

2. The spacecraft coordinates (right ascension, declination, and range) should be known to about $4''$ and 100 km.

3. Data downlinks should be frequent and rapid, since most transient sources benefit from rapid follow-up observations.

The first two requirements rarely pose any major problems, but the third can be difficult to achieve for planetary missions, because light travel times can reach several thousand seconds, and some missions have very little data recovery in their cruise phases.

Calibration is a crucial aspect of any experiment. There are two ways to approach this with an interplanetary network. The first is to send commands to the spacecraft at precisely known times and record their arrival on board. With a knowledge of the light travel time, this can be used to verify the spacecraft clock and range. A more complete, end-to-end calibration is to use the network to triangulate sources whose precise positions are known by other means, such as GRBs with X-ray or optical counterparts, or soft gamma repeaters (SGRs). This calibrates not only the spacecraft clocks, but also their ephemerides, as well as the on-board data handling and ground-based data reduction techniques. Both methods should be used wherever possible.

Results and discoveries

Even before the formation of a network for astrophysical purposes, the *Vela* spacecraft discovered GRBs (Klebesadel et al 1973) and arrival-time analysis was used to get coarse positions for them. Shortly after the formation of the first interplanetary network in 1977, the first giant magnetar flare, from the SGR SGR0525-66 was triangulated to a small uncertainty box, and its source was identified as being contained within the N49 supernova remnant in the Large Magellanic Cloud (Cline et al 1980; Evans et al 1980). The discovery of one of the SGRs (Atteia et al 1983) and the most precise localizations of all of them (Cline et al 1980; Evans et al 1980; Hurley et al 1999a,b,c) have been the results of triangulation. Giant outbursts from Cygnus X-1 were discovered and localized with the help of triangulation (Golenetskii et al 2003), finally fulfilling the suggestion of Giacconi (1972). Until the advent of coded mask imaging detectors, the only way to derive the precise positions of γ-ray burst sources was by triangulation using interplanetary networks.

Single-experiment systems

A single experiment can also monitor a large fraction of the sky. In low Earth orbit instruments can be larger and more sensitive than those which can be placed on interplanetary spacecraft. Compton telescopes, discussed in Chapter 11 (Schönfelder and Kanbach 2010), are one method, and experiments which rely on anisotropic detectors are another. An idealized detector with a flat surface and negligible thickness has a cross-sectional area which is proportional to the cosine of the arrival direction. The ratios of the responses of three or more non-coplanar detectors on a single spacecraft give the arrival direction of a burst. The accuracy with which an uncertainty box can be derived depends on the counting statistics of the detections (rather than the time structure of the light curves) and the systematic uncertainties in the detector calibrations. In addition, backscattering from the spacecraft and, in the case of a low Earth orbiter, the atmosphere, must be taken into account.

The first use of this method was aboard the *Venera 11* and *12* interplanetary spacecraft which were launched in 1977 (the Konus experiment, Mazets and Golenetskii 1981). The detectors were six 50 cm^2 scintillators. In 1991 the method was used aboard the *CGRO* Burst and Transient Source Experiment (BATSE), which utilized eight 2025 cm^2 scintillators. For intense GRBs, the statistical uncertainties were practically negligible, while systematics limited the uncertainty-box sizes to 1.6°, the best accuracy which the method has achieved to date (Briggs et al 1999). Earth-occultation was used to supplement the monitoring capabilities (Ling et al 2000). In 1996, the method was used again for the four 1100 cm^2 scintillators comprising the anticoincidence system of the Phoswich Detection System aboard *BeppoSAX* (the Gamma-Ray Burst Monitor, Guidorzi et al 2004).

The first SGRs were discovered with the Konus experiments (Mazets et al 1979a,b). SGR1627-41 and the bursting pulsar GROJ1744-28 were discovered by BATSE (Woods et al 1999; Kouveliotou et al 1996), and thanks to its great sensitivity, BATSE provided the first unambiguous evidence for the isotropic distribution of GRBs (Meegan et al 1992).

Outlook

There will always be a need for continuous, all-sky monitors, and both single- and multiple-experiment systems will continue to be utilized for the foreseeable future. The Gamma Burst Monitor aboard *Fermi* launched in 2008, is an example of the former, and the 3^{rd} interplanetary network, which began operations in 1990, will continue to operate for at least several more years. The two systems, in fact, work well together; the single-experiment systems have the advantages of good sensitivity and rapid response, while multiple detector systems can refine the uncertainty boxes derived by the single detectors systems (Hurley et al 1999d).

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