INTEGRAL CAPABILITIES FOR FAINT GAMMA-RAY BURSTS

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1. INTRODUCTION

The study of gamma-ray bursts (GRBs) is just one of the many objectives of INTEGRAL. But developments in the GRB-field over the past few years have made it increasingly clear that INTEGRAL may make a very significant contribution to this fast developing field. We know today that most GRBs originate in the very distant universe. In fact, we believe that their intrinsic brightness allows us to detect these events at epochs corresponding to the formation of the earliest stellar populations. Thus they may be used as probes into the first stages of star formation and their spectra may reveal the early heavy-element enrichment of the interstellar medium. Lamb & Reichart (2000) claim that GRBs could be originated by primitive stellar populations up to redshift $z \sim 50$.

2. THE NEEDS OF THE GRB COMMUNITY

The discovery of the GRB afterglow, in X-rays, radio and the optical (Costa et al. 1997, van Paradijs et al. 1997) have finally provided us the long sought tool for associating a burst with a concrete object in the sky. Although the duration of the afterglow is measured in hours or days instead of the seconds which are characteristic of the bursts themselves, there are still two mandatory requirements for successful afterglow searches: accurate initial positions and rapid dissemination of the alerts. The successes achieved by the SAX team have been based on the positions accurate to maybe 10 square arcminutes and delays of a few hours (Boella et al. 1997). Lately, several afterglows have also been detected based on arcminute positions provided by the IPN with delays of the order of 24 hours (Hurley et al. 2000a, 2000b). No doubt, IPN positions will continue to be useful and warrant follow up for a number of years to come, but if we want to fully exploit the potential of high resolution spectroscopy of the intense phases of the afterglows - and if want to check in higher detail our models for the afterglow process itself - then we must provide arcminute positions with delays of only a few minutes or even less.

3. INTEGRAL CAPABILITIES

INTEGRAL will be the first gamma-ray spacecraft which combines imaging instruments of high precision and a continuous real time telemetry link. In Table 1 we compare in a simple minded way a number of different space missions with capabilities for GRB research. The missions are divided in three groups depending on their energy range. In the first group the INTEGRAL/IBIS sensitivity is normalized respect to Swift sensitivity, and in the second group the INTEGRAL/JEM-X and SAX sensitivity is given respect to the HETE-2 one. For consistency we have...
Table 1. Capabilities of several missions.

| Mission/instrument         | Area cm$^2$ | Coverage % of 4π str. | Relative sensitivity | Energy (keV) | Orbit efficiency | GRBs detected per year |
|----------------------------|-------------|----------------------|---------------------|-------------|------------------|------------------------|
| Swift                      | 5200        | 16                   | 1.0                 | 15 to 150   | 0.6              | 300                    |
| INTEGRAL/IBIS(ISGRI)       | 3000        | 1                    | 3.0                 | 15 to 150   | 0.8              | 35                     |
| HETE-2                     | 360         | 12                   | 1.0                 | 2 to 25     | 0.5              | 25                     |
| INTEGRAL/JEM-X             | 1000        | 15.4                 | 4.0                 | 2 to 25     | 0.8              | 2                      |
| SAX/WFC                    | 530 (×2)    | 2 (×2)               | 3.0                 | 2 to 30     | 0.5              | 12                     |
| Rømer/WATCH                | 95 (×4)     | 25 (×4)              | 1.0                 | 6 to 100    | 0.6              | 70                     |
| CGRO/BATSE                 | 2000 (×8)   | 65                   | 4.3                 | 50 to 300   | 0.6              | 300                    |

- The GRB rate is proportional to the star formation rate (SFR) in the universe. The SFR considered are the one given by Rowan-Robinson (1999) for $z < 5$ and the one calculated by Gnedin & Ostriker (1997) for $z ≥ 5$. (See Fig.1).

Figure 1. The plot shows the Star formation rate (SFR) in the universe as a function of the redshift. The dashed line represents the SFR derived by numerical simulations by Gnedin & Ostriker (1997) for $z ≥ 5$. The solid line shows the SFR at the $z < 5$ region based on Observational estimates (Rowan-Robinson 1999). The transition between the two regions have been smoothed.

4. DETECTABILITY OF A FAINT POPULATION OF GRBS

We have selected the most sensitive future missions (INTEGRAL/IBIS, Swift and HETE-2) to calculate their capabilities of detecting a high redshift population of bursts. For the estimate of the number of GRBs that these missions will detect, we assume:

- The GRB Luminosity function is given by:

$$ S(L) = \begin{cases} 
L^\beta & L_{\text{min}} < L < L_{\text{max}} \\
0 & \text{Otherwise} 
\end{cases} $$

being $L$ the peak photon luminosity and $\beta$ the luminosity function index. $L_{\text{min}}$, $L_{\text{max}}$ determine the width of the luminosity function.

- Although the effect of several universe models have been tried, the cosmological parameters presented in this paper are $\Omega_m=0.3$, $\Omega_\Lambda=0.7$, $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$.
According to the former assumptions the differential GRB detection rate at a given photon peak flux $P$ at the detector (ph cm$^{-2}$s$^{-1}$) is given by the following convolution integral;

$$N_{GRB}(P) = C \Omega e \int_{0}^{\infty} R_{GRB} S(L) dL$$  

(1)

e is the efficiency of the orbit, $\Omega$ is the instrumental coverage of the sky and $R_{GRB}$ is the GRB detection rate if they were standard candles, i.e:  

$$R_{GRB} = \frac{SFR(z) dV(z) dz}{dz}$$

being $V$ the comoving volume and $SFR(z)$ the star formation rate. The value of the proportionality constant $C$ is unknown. Fig 2. shows $N_{GRB}(P)$ as well as the detection thresholds of several instruments.

Figure 2. Differential peak photon flux distribution of GRBs. The solid curve shows the differential peak photon flux distribution if all redshifts are considered, i.e. $N_{GRB}(P|0)$. The dashed curves represent the differential peak photon flux distribution of GRBs when only GRBs with $z > z_{edge}$ are taken into account, i.e. $N_{GRB}(P|z_{edge})$. The vertical lines represent the detection thresholds for the different instruments, showing the arrows the detectability region.

The relationship between $L$, $z$ and $P$ is given by the next expression;

$$P = \frac{L}{4\pi D(z)^2(1+z)^\alpha}$$

Where $D(z)$ is the comoving distance. In our calculations different values of $\alpha$, $L_{min}$, $L_{max}$ and $\beta$ are considered. The values of $\alpha$, $\beta$, $\Omega_\Lambda$ and $\Omega_m$ do not change the final result qualitatively. Instead the values of $L_{min}$, $L_{max}$ are very relevant to the determination of the number of high redshift GRB detections. We consider the most pessimistic case where $L_{min} = 10^{57}$ ph s$^{-1}$ and $L_{max} = 10^{58}$ ph s$^{-1}$ (according to the GRB redshifts measured so far the GRB luminosity function seems to be wider). We can calculate the contribution to the integral (1) by the GRBs with redshift larger than $z_{edge}$;

$$N_{GRB}(P|z_{edge}) = C \Omega e \int_{0}^{\infty} H(z(L), z_{edge}) R_{GRB} S(L) dL$$

Where $H(z(L), z_{edge})$ is a step function that vanishes unless $z(L) > z_{edge}$. Obviously, $N_{GRB}(P|0) = N_{GRB}(P|0)$, and $\frac{N_{GRB}(P|z_{edge})}{N_{GRB}(P|0)} \leq 1$. Finally we can calculate the number of GRBs detected above a given instrumental photon flux threshold $P_{ins}$ that have redshifts larger than $z_{edge}$;

$$N_{GRB}(z_{edge}|P_{ins}) = \int_{P_{ins}}^{\infty} N_{GRB}(P|z_{edge}) dP$$

The ignorance of the proportionality constant $C$ prevents us to derive an absolute value for $N_{GRB}(z_{edge}|P_{ins})$. However, we can determine the relative quantity $\frac{N_{GRB}(z_{edge}|P_{ins})}{N_{GRB}(0|P_{ins})}$, which provide us the proportion of detections that have a redshift larger than $z_{edge}$ (see Fig. 3).

Figure 3. Relative number of detections as a function of the redshift. This plot shows for several missions/instruments the fraction of the detected GRBs that have a redshift larger than $z_{edge}$.
5. IBIS vs. SWIFT; COMPARISON OF THE NUMBER OF THE GRB DETECTIONS

As it is shown in Fig. 3, ~10% of the GRBs detected by IBIS will have a redshift larger than 8.4. For Swift the z > 8.4 population will be just ~ 4% of the total number of detections. HETE-2 is the less sensitivity detector, being constrained to detect GRBs with redshifts z < 6. Therefore we will not consider HETE-2 for the further study aimed to calculating the relative number of detections as a function of the redshift. We will be centered in comparing IBIS and Swift capabilities. Besides, as we noted, the similar energy range and detector technologies of IBIS and Swift guarantee a reliable calculation of this fraction.

For determining the relative number of detections between two experiments, A and B, the next expression has to be calculated:

\[ f_{A/B}(z_{edge}) = \frac{\int_{z_{edge}}^{\infty} \rho_{A}(z)F(z)P(z)dz}{\int_{z_{edge}}^{\infty} \rho_{B}(z)F(z)P(z)dz} \]

This function will give the relative number of GRB detections with z > z_{edge}. We have applied the former expression to derive the fraction \( f_{IBIS/Swift} \) as a function of the GRB redshift.

If we consider \( z_{edge} = 0 \) the fraction \( f_{IBIS/Swift} \) gives us the fraction of GRBs detected with z > 0, i.e, all the detections independently of their redshifts are considered. We obtain a value of \( f_{IBIS/Swift}(0) = 1/7.8 \) (see Fig. 4), which is consistent with the value of \( f_{IBIS/Swift} \) derived from last column of Table 1. The large field of view (FOV) of Swift in comparison to IBIS makes that for \( z_{edge} < 11.6 \), \( f_{IBIS/Swift} < 1 \). Instead, for further redshifts than 11.6, IBIS sensitivity becomes the governing factor and \( f_{IBIS/Swift} > 1 \).

6. CONCLUSION

Fig. 3 shows \( \frac{N(z_{edge},P_{max})}{N(0,P_{max})} \) for HETE-2, IBIS, and Swift. For IBIS the tail of \( \frac{N(z_{edge},P_{max})}{N(0,P_{max})} \) extends to redshifts \( z_{edge} > 11 \). Swift and HETE-2 would detect a closer population of burst, specially HETE-2 would be constrained to redshifts \( z_{edge} < 6 \).

If we consider all the GRBs (\( z_{edge} > 0 \)) the detection fraction \( f_{IBIS/Swift} = 1/7.8 \). Thus, at low redshifts the large FOV of Swift in comparison to INTEGRAL instrumentation governs the number of detections. However, at high redshifts the better sensitivity of IBIS makes the fraction of detections \( f_{IBIS/Swift} > 1 \) (for redshifts \( z_{edge} > 11.6 \), \( f_{IBIS/Swift} > 1 \), see Fig. 4). Although JEM-X FOV and sensitivity are less suitable than the one of IBIS to detect GRBs, the spectral peak of the high redshift GRBs (usually at 500–1200 keV) will be in the detection range of JEM-X. Therefore JEM-X will be also a very valuable tool to study the high redshift GRBs.

In conclusion, the capabilities of studying GRBs of JEM-X and IBIS on board INTEGRAL are complementary to the ones of missions like Swift and HETE-2 specially devoted to prompt localizations of GRBs. Whereas Swift and HETE-2 would detect more GRBs than INTEGRAL, JEM-X and IBIS instruments would detect very high redshift GRBs unreachable to the above mentioned missions. Therefore, INTEGRAL and specially IBIS will be a very valuable tool to trace the SFR rate in the early universe.

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