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Joint Astrophysics Nascent Universe Satellite:

utilizing GRBs as high redshift probes

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Abstract. The Joint Astrophysics Nascent Universe Satellite (JANUS) is a multi-wavelength cosmology mission designed to address fundamental questions about the cosmic dawn. It has three primary science objectives: (1) measure the massive star formation rate over $5 \leq z \leq 12$ by discovering and observing high-z gamma-ray bursts (GRBs) and their afterglows, (2) enable detailed studies of the history of reionization and metal enrichment in the early Universe, and (3) map the growth of the first supermassive black holes by discovering and observing the brightest quasars at $z \geq 6$. A rapidly slewing spacecraft and three science instruments – the X-ray Coded Aperture Telescope (XCAT), the Near InfraRed Telescope (NIRT), and the GAmma-ray Transient Experiment for Students (GATES) – make-up the JANUS observatory and are responsible for realizing the three primary science objectives. The XCAT (0.5–20 keV) is a wide field of view instrument responsible for detecting and localizing ~60 $z \geq 5$ GRBs, including ~8 $z \geq 8$ GRBs, during a 2-year mission. The NIRT (0.7–1.7 μm) refines the GRB positions and provides rapid ($\leq$ 30 min) redshift information to the astronomical community. Concurrently, the NIRT performs a $20,000$ deg^2 survey of the extragalactic sky discovering and localizing ~300 $z \geq 6$ quasars, including ~50 at $z \geq 7$, over a two-year period. The GATES provides high-energy (15 keV – 1.0 MeV) spectroscopy as well as 60–500 keV polarimetry of bright GRBs. Here we outline the JANUS instrumentation and the mission science motivations.

Key words. Space vehicles – Space vehicles: instruments – Gamma-ray burst: general – early Universe – dark ages, reionization, first stars

1. Introduction

Arguably, the final frontier of observational astrophysics is the period known as the cosmic dawn ($7 \lesssim z \lesssim 13$). It is this period in our history that was highlighted in the 2010 Astrophysics Decadal Survey (NRC 2010) as one of the top priorities for study. During this period the Universe began the transition from a

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composition of mostly neutral hydrogen (H I) to ionized hydrogen (H II). It is believed that the dominant source of this reionization was the first gravitationally bound objects, primarily early massive stars (Barkana 2006). There are many questions related to these early stars: how and when did they form; what environment did they live in; how did they contribute to future generation of stars; what was the star formation rate (SFR) at this early epoch; and how did it evolve over time?

Our current understanding of the answers to these questions primarily comes by means of numerical simulations. These simulations paint a picture as described below, although the presentation here is somewhat abbreviated.

Around 200 million years after the Big Bang (Bromm et al. 2009), baryonic matter, primarily consisting of atomic H and He, began falling into small (10^5–10^6 $M_\odot$) dark matter dominated haloes (Abel et al. 2007; Gao & Theuns 2007). As these clouds of baryonic matter began collapsing, they warmed to temperatures > 1000 K. In these dense hot clouds, some of the H-atoms paired and created molecular hydrogen (H_2), which acted as a cooling agent. As the gas cooled to ~200 K it also caused further contraction of the gas cloud eventually collapsing to the point where the first stars turned on (Abel et al. 2000). These firsts stars were very massive (60–300 $M_\odot$; Bromm et al. 2002, 2009), with large luminosities (~2–10×10^6 $L_\odot$) and radii (~5–10 $R_\odot$), metal free (Loeb 2010), and possibly very high spin rates (Chiappini et al. 2011). This combination of large mass, high spin rates, and low metallicity points to a these early stars possibly ending their lives as gamma-ray bursts (GRBs; Woosley & Heger 2006). The death of these massive stars could have produced the heavier elements that were later recycled in the next generation of stars (Heger & Woosley 2002).

As tantalizing as these numerical results are, very little observational evidence has been obtained, thus making it difficult to verify the numerical findings. A current census of spectroscopically confirmed $z > 6$ objects consists of: three GRBs, including GRB 090423 at $z = 8.2$ (Tanvir et al. 2009); ~35 quasars, which includes ULAS J1120+0641 at $z = 7.085$ (Mortlock et al. 2011); and ~30 galaxies plus the most distant galaxy in the sample, UDFy-38135539 at $z = 8.5549$ (Lehnert et al. 2010). In addition, a photometric redshift was determined for GRB 090429B (Cucchiara et al. 2011) and UDFy-39546284 (Bouwens et al. 2011) at z~9.4 and z~10, respectively.

Despite the paucity of these samples, GRBs, quasars, and galaxies have been used to infer the nature of the early Universe (e.g., measure the SFR; Wanderman & Piran 2010; Wang et al. 2011; Bouwens et al. 2009), with great disparity between the different models (e.g., Yüksel et al. 2008). As cosmological probes, each of these object types have pros and cons (see Table 1). As illustrated in Table 1, if GRBs can be captured when they are bright, they have a distinct advantage over quasars and galaxies as cosmological probes. In addition, their host galaxies are not biased with respect to the host's luminosity. Current high-z galaxy surveys only detect the bright end of the luminosity function; therefore, they underestimate the SFR – even the *James Webb Space Telescope* will not be able to detect faint high-z galaxies (Barkana & Loeb 2000). Because of the physical and observational challenges associated with using quasars and galaxies as high-z probes, GRBs may be the only way to perform a statistically significant $z > 8$ survey in the foreseeable future.

However, current capabilities for observing these high-z beacons is limited. The need exists to probe further back in redshift space and to gather an ~10× larger sample.

2. Why Not *Swift*?

The *Swift* Gamma-Ray Burst Mission (Gehrels et al. 2004) has transformed the field of GRBs. Included in its many revolutionary discoveries are: flaring in light curves due to energy injection from the central engine (e.g., Burrows et al. 2005), observations of short GRB afterglows (e.g., Gehrels et al. 2005; Roming et al. 2006) that challenged previous held beliefs on their origins (cf. Fox & Roming 2007), a connection between the prompt central engine and activity in early x-ray afterglows (O'Brien et al. 2006), "canonical" x-ray afterglows (e.g.,

Table 1. Characteristics of High-z Probes

Characteristics	GRBs	quasars	galaxies
Persistent/Fading Source (P/F)	F	P	P
Luminosity ($log\mathrm{L}_{\odot}$)	~19	~13	~10
Non-thermal/Thermal Spectrum (N/T)	N	T	T
Increasing/Decreasing in Frequency (I/D)	I*	D	D

*cf. Yüksel et al. (2008); Qin et al. (2010)

Nousek et al. 2006), two component jets (e.g., Oates et al. 2007; Racusin et al. 2008), observation of a nearby damped Ly-α absorber (DLA) in a GRB afterglow (Kuin et al. 2009), and a determination that at least some short GRBs are the result of a compact merger (e.g., Berger 2009).

Notwithstanding these successes, *Swift* has struggled in meeting one of its primary science objectives: to "use GRBs to study the early universe out to $z > 10$" (Gehrels et al. 2004). In its almost seven years of operations, *Swift* has only discovered three GRBs with verified redshifts of $z > 6$ (e.g., Kawai et al. 2006; Greiner et al. 2009; Tanvir et al. 2009). Why is this? The answer lies in the fact that *Swift* was not optimized for high-z observations. This limitation comes from three primary mission configurations: (1) the *Swift* Burst Alert Telescope (BAT; Barthelmy et al. 2005) is not optimized in the correct energy range, (2) the *Swift* Ultra-Violet/Optical Telescope's (UVOT; Roming et al. 2005) response is not red enough, and (3) there is no on-board redshift capability.

The BAT is optimized for detecting ~40–80 keV bursts, which equates to $\sim 1.75 < z < 4.5$. Indeed, the average redshift of *Swift* bursts is $\langle z \rangle = 2.19$ (Jakobsson et al. 2006)[1]. Recent work reveals that the optimal energy band for detecting high-z bursts is $\lesssim 30$ keV (Burrows et al. 2011).

The UVOT's reddest response is ~8000 Å, which equates to the detecting of the Ly-α edge in the GRB afterglow out to a $z \sim 5.1$. An examination of the second UVOT afterglow catalog reveals that of the ~200 GRBs with afterglows, the highest redshift is GRB 100219A at $z = 4.67$ (Roming et al. 2011). In order to probe to $z \approx 10$, the instrument response needs to be pushed out to > 1.4 μm.

[1] This value continues to be updated at http://www.raunvis.hi.is/ pja/GRBsample.html

Table 2. Confirmed Spectroscopic $z > 6$ GRBs

GRB	$t_{\mathrm{Photo-z}}$ (hrs)	$t_{\mathrm{Spectra-z}}$ (hrs)	z
050904	10	84	6.3
080913	10	11	6.7
090423	7	24	8.2

Swift provides arcsecond and sub-arcsecond positional information but does not have the capability for providing burst redshifts. These redshifts are provided by the ground-based community, which has proven to be cumbersome and inadequate method. Based on limited past experience with high-z bursts (see Table 2), it typically takes ~10 hrs to obtain a photometric redshift, followed by an additional ~14 hrs to measure the redshift spectroscopically. By this time, the afterglow has usually faded below levels that are useful for doing science. In order to study a large sample of GRBs during the cosmic dawn, ground-based telescopes need to have redshift information in ~30 min.

3. Joint Astrophysics Nascent Universe Satellite

A proposed solution to addressing these limitations is the Joint Astrophysics Nascent

Universe Satellite. The mission is designed around observations of high-z objects with three primary science objectives, three science instruments, and two observing modes, as described below.

3.1. JANUS Science Objectives

The three primary JANUS science objectives are: (1) measure the massive star formation rate (SFR) over $5 \leq z \leq 12$ by discovering and observing high-z GRBs and their afterglows; (2) enable detailed studies of the history of reionization and metal enrichment in the early Universe; and (3) map the growth of the first supermassive black holes by discovering and observing the brightest quasars at $z \geq 6$.

JANUS simulations indicate that ~60 bursts at $z \geq 5$ (~8 at $z \geq 8$) over a two-year mission will be identified, with burst positions, fluxes, and redshifts transmitted to the astronomical community for most bursts in < 30 min (initial positions and fluxes will be transmitted much earlier, while the redshift is being obtained). These notifications will facilitate rapid ground-based observations of the afterglows while they are still bright, thus allowing a measure of the ionized fraction in the interstellar medium and the metal content in the circumburst environment. Concurrently, JANUS will localize ~300 quasars at $z \geq 6$ (~50 at $z \geq 7$) thus providing a large statistical sample for studying these early massively collapsed objects.

3.2. JANUS Instruments

The JANUS observatory is composed of four major components: the spacecraft, the X-ray Coded Aperture Telescope (XCAT; Falcone et al. 2010), the Near InfraRed Telescope (NIRT), and the GAmma-ray Transient Experiment for Students (GATES). The placement of the instruments onto the spacecraft is shown in Fig. 1. The spacecraft provides a stable platform from which the instruments can observe, rapid slews to GRBs (50 deg in 100 s), and rapid communication with the ground.

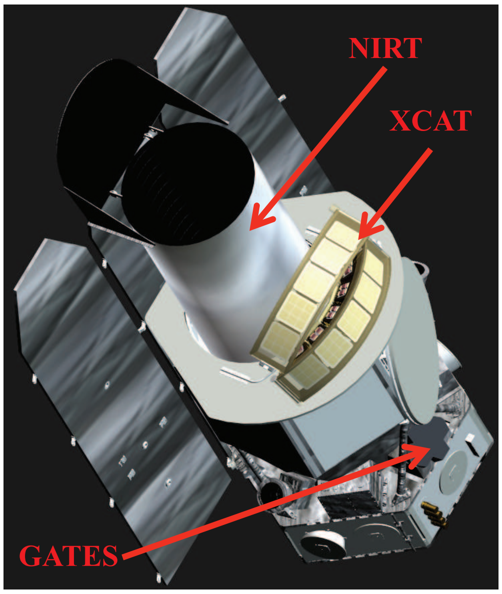

Fig. 1. The JANUS Observatory with the location of each instrument identified.

The primary function of the XCAT is to detect high-z ($z > 6$) GRBs and to provide ~sub-arcmin localizations. The XCAT (Fig. 2) is a coded aperture telescope that is sensitive in the 0.5–25 keV range. The telescope consists of ten modules that are arranged in a 2×5 caterpillar format that provides a field-of-view of ~4 sr. Since high-z GRBs are rare, breadth is more important than depth; therefore, a large field-of-view is critical. Bursts are localized to 40–70 arcsec using a triggering algorithm similar to that used on the *Swift* BAT. These instrument parameters have been optimized for finding high-z GRBs (Burrows et al. 2011).

The primary function of the NIRT is to provide sub-arcsecond localizations and redshifts of $z > 6$ GRBs and quasars. The NIRT (Fig. 3) is of a Ritchey-Chrétian design with a 55-cm aperture. The detector is sensitive in the 0.7–1.7 μm range and has a 0.36 deg^2 field-of-view, thus enabling a survey of the entire extragalactic sky for quasars in two years while providing ample spatial coverage of the XCAT's GRB positional uncertainty. NIRT burst positions are localized to sub-arcsecond accuracy. The NIRT performs direct imaging and low-

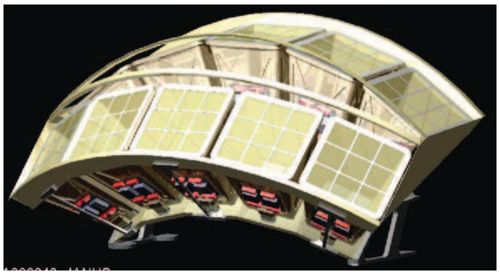

Fig. 2. The JANUS X-ray Coded Aperture Telescope (XCAT).

resolution ($R \sim 16$ at 1.2 μm) spectroscopy via the means of an objective prism. Burst position and redshift information is sent to the ground in < 30 min. Since NIRT observations are done above the Earth's atmosphere, the near-IR background is orders of magnitude lower and telluric lines are eliminated, thus NIRT magnitude limits are considerably lower as compared to comparable aperture instruments.

The GATES (Fig. 4) instrument is a student project based on the Gamma-RAy Polarimeter Experiment (GRAPE; McConnell et al. 2009). The GATES detector is an array of individual plastic and CsI scintillator elements, each independently read out by a Si photomultiplier. The array operates in the 15 keV – 1.0 MeV band in a photon-counting and spectroscopic mode, thus capturing the peak energies (E_p) of bright GRBs. It also measures the polarization in the 60–500 keV range of bright GRBs. The field-of-view is ±60 deg.

3.3. JANUS Observing Modes

JANUS has two primary observing modes: survey and burst. In the survey mode, the NIRT performs an objective prism survey of the extragalactic sky ($20,000$ deg^2) to a limiting magnitude of $J = 20$ (4σ) in search of $z > 6$ quasars. A deeper survey of 200 deg^2 will provide a limiting magnitude of $J = 21.9$ (4σ).

While the NIRT is performing this survey, the XCAT is scanning the sky for GRBs. When a GRB is localized, the NIRT survey is interrupted and the spacecraft slews the NIRT boresite to the position of the GRB. The NIRT takes simultaneous images and spectra of the afterglow which are then telemetered to the ground. The GATES provides E_p and polarimetry information on the brighter bursts. Burst position, flux, light curves (LCs), and spectra are rapidly transmitted (see Table 3) to the GRB Coordinate Network (Barthelmy et al. 1995, 1998).

Fig. 3. The JANUS Near InfraRed Telescope (NIRT).

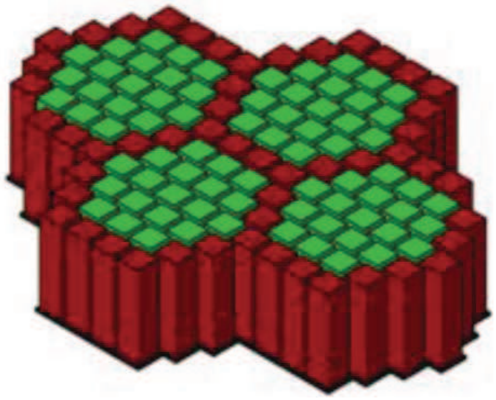

Fig. 4. The JANUS GAmma-ray Transient Experiment for Students (GATES).

Table 3. GRB Observation Timeline

Event	Time Since Trigger (s)
GRB Trigger	0
X-ray position to GCN	15
X-ray flux to GCN	15
Init. X-ray LC to GCN	100
γ-ray spectra to GCN	120
X-ray LCs to GCN ($\times$10)	120–280
NIRT position to GCN	1140
NIRT flux to GCN	1140
NIRT spectra to GCN	1140
Redshift to GCN	1200

4. Conclusions

If the capability for acquiring a target and disseminating a redshift is available, GRBs are one of the best ways for observing the early ($6 \lesssim z \lesssim 13$) Universe. The JANUS is optimized for detecting and observing these high-z GRBs and their afterglows, as well as for uncovering high-z quasars.

Based on mission simulations, it is anticipated that JANUS will directly provide the following results: measure the massive-SFR in the infant Universe, determine the role of high mass stars on reionization, and map the growth of super-massive black holes in $z > 6$ quasars. Because of its softer energy response, the XCAT will also discover and localize low-z, low-luminosity GRBs that are associated with supernovae. JANUS will also facilitate other ground- and space-based science endeavors, co-jointly delivering such potential results as: localizations of faint high-z galaxies, a realization of the amount of metal enrichment in early Universe star-forming regions, and a determination if PopIII stars explode as GRB/pair-instability supernovae.

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