THE RAPID IMAGER AND SPECTROGRAPH (RIMAS): A NEW WINDOW INTO THE HIGH-REDSHIFT UNIVERSE

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1. Abstract

RIMAS is a new NIR instrument designed expressly to identify high-redshift γ-ray bursts (GRBs) from *Swift*, scheduled to be installed on the 4.3 m Discovery Channel Telescope (DCT) in the first half of 2015. RIMAS can operate in and switch rapidly (10s of seconds) between three modes: 1) simultaneous 2-band imaging; 2) high-throughput, $R \approx 25$ NIR spectroscopy; 3) high-resolution ($R \approx 4500$), cross-dispersed echelle spectroscopy providing simultaneous coverage from 0.9–2.4 μm. Unlike most classically scheduled facilities, RIMAS will be continuously available for rapid-response ($\Delta t \lesssim$ minutes) ToO observations. By Cycle 11, RIMAS will be routinely obtaining rapid multi-color photometry and NIR spectra of Swift afterglows to measure their redshifts and constrain properties of their host galaxies and the surrounding IGM.

2. Description of the Proposed Program

A) Scientific Rationale:

Understanding both the precise time history and the sources responsible for cosmic reionization remains one of the most sought-after goals of modern cosmology. The discovery of Gunn-Peterson troughs in the spectra of $z \gtrsim 6$ quasars (QSOs[1]) implied at least a modest neutral H fraction ($x_{\rm H\,I}$) at this time. However, observations of the cosmic microwave background (CMB[2]) indicate a significantly larger characteristic reionization redshift ($z_{\rm reion} \approx 10$). It may be possible to reconcile these two seemingly contradictory observations if reionization were to occur slowly with a large degree of small-scale variation. Many more sightlines are needed to test this hypothesis, something not possible for QSOs with current instrumentation.

While both QSOs and the CMB have been used to study reionization for some time, long-duration γ-ray bursts (GRBs) are a relatively new probe of the high-redshift universe (e.g.,[3]). GRBs offer several theoretical advantages over QSOs for constraining $x_{\rm H\,I}$ near the epoch of reionization: 1) though short-lived, their afterglow emission can significantly outshine even the brightest QSOs (e.g.,[4,5,6]); 2) the power-law afterglow spectral energy distributions are significantly simpler to model than QSOs, leading to more precise $x_{\rm H\,I}$ measurements[7]; 3) GRBs are not biased towards the most massive halos[7] because they result from the core-collapse of a single massive star.

Thanks to more than a decade of painstaking effort from the community, we are finally on the cusp of using GRBs to make meaningful measurements of the neutral H fraction at cosmologically interesting redshifts ($z \gtrsim 7$). The discovery of GRB 090423 at $z \approx 8.2$[8,9], the most distant spectroscopically confirmed source in the universe (Figure 1), along with the measurement of a photometric redshift of $z \sim 9.4$ for GRB 090429B[10], unambiguously establish that GRBs explode and are detectable at the relevant redshifts of interest. In fact we have relatively precise constraints on the rate of such events from unbiased *Swift* samples: $\approx$ a few percent of the *Swift* population resides at $z \gtrsim 7$ (1–2 events per year;[11,12]). Furthermore, high signal-to-noise ratio (SNR) spectroscopy of the $z = 5.913$ GRB 130606A and $z = 6.33$ GRB 140515A (Figure 1) enabled for the first time strict upper limits on the neutral H fraction from the profile of the Lyα red damping wing[13,14,15,16].

Despite these remarkable successes, as a community we still lack the ultimate prize: meaningful constraints on $x_{\rm H\,I}$ at a redshift of interest for reionization ($z \gtrsim 7$). Given that *Swift* has likely detected $\gtrsim 10$ events over the course of its lifetime at these distances, the bottleneck is clear: a lack of promptly available NIR imaging and spectroscopy on moderate/large aperture telescopes. At $z \gtrsim 7$, rest-frame Lyα is redshifted into the observer-frame NIR. While many promptly available optical facilities automatically respond to *Swift* GRB alerts, the number of *readily available* NIR imagers, and, to an even larger degree, spectrographs, is remarkably small [RATIR, GROND, NIRI (Gemini), X-SHOOTER (VLT)]. Without NIR capabilities, it is nearly impossible to distinguish between events that are optically faint because they are obscured by dust (a significant fraction of the *Swift* population;[17,11,12]) and true high-redshift GRBs, let alone measure $x_{\rm H\,I}$ from the red wing of Lyα.

Here we request funding to assist with the commissioning of the Rapid infrared IMAger and Spectrograph (RIMAS), a new NIR imager and spectrograph to be installed and made *continuously available* on the 4.3 m Discovery Channel Telescope (AZ) in early 2015. Through automated ToO observing, RIMAS will be able to obtain photometric and spectroscopic measurements minutes after a *Swift* trigger.

B) Immediate Objective:

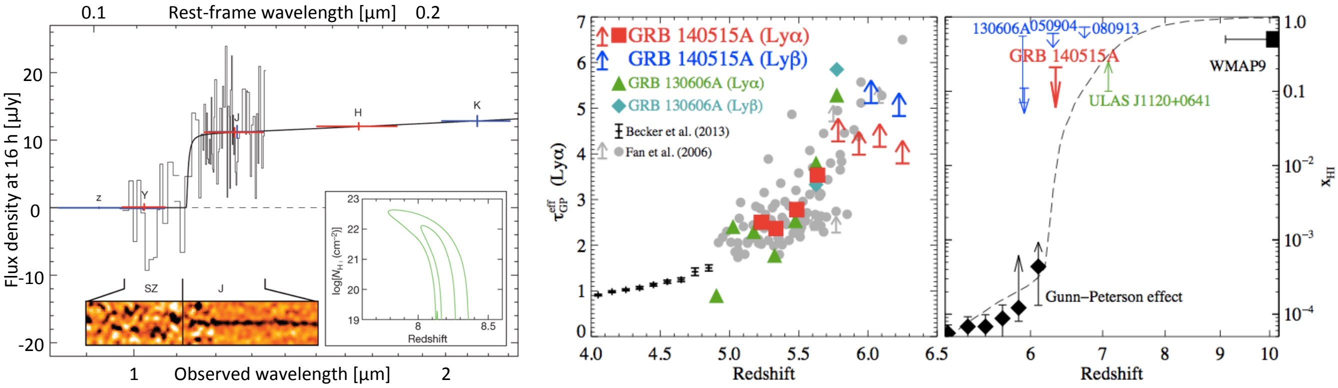

Figure 1: *Left panel*: NIR spectrum of the afterglow of the $z = 8.2$ GRB 090423 [8], obtained with ISAAC on the VLT at a full 16 hr after the burst trigger time. While the sharp break in the spectrum (consistent with that obtained from broadband photometry) indicates a redshift of $z \approx 8.2$, the low SNR precludes meaningful constraints on $x_{\rm H\,I}$. *Right panel*: Redshift evolution of the IGM from GRBs and quasars. Recent observations of GRB 140515A (blue and red [16]) and GRB 130606A (cyan and green [13]) are compared with limits from quasar observations. Even with just a small number of sightlines, GRBs can provide powerful constraints at redshifts $z \lesssim 6$. However, thus far, no high SNR spectra of a GRB afterglow has been obtained at a redshift directly probing the epoch of reionization ($z \gtrsim 7$).

Our principle objective is quite straightforward: by the end of Cycle 11, we intend for RIMAS to be routinely obtaining rapid multi-color photometry and (as appropriate) NIR spectroscopy of *Swift* afterglows to measure their redshifts and constrain properties of their host galaxies and the surrounding IGM. To better understand the level of effort required to reach this point, we first provide an overview of the instrument design and a summary of the current status.

Design Overview: RIMAS is a collaborative effort between Goddard Space Flight Center, the University of Maryland, and Lowell Observatory. The instrument is being designed for the recently commissioned 4.3 m Discovery Channel Telescope (DCT). RIMAS will be installed on one port of the DCT "instrument cube", where a pick-off dichroic beamsplitter will allow users to switch between multiple instruments with an overhead of only seconds and simultaneously image visible wavelengths with the Large Monolithic Imager (LMI[1]).

RIMAS has three operating modes: imaging, low spectral resolution (R $\approx$ 25) and a high resolution mode ($R \approx 4500$). The spectral coverage spans from 0.9–2.4 μm (Y-, J-, H-, and K-band). The optical layout has two arms with two detectors allowing for a simultaneous imaging in two bands, Y or J in one arm of the instrument, and H or K in the other. The designed ensquared energy is near the diffraction limit, with one pixel corresponding to $0.35''$, and a field-of-view of $3' \times 3'$ (well matched to BAT localizations, so that we can begin imaging even before XRT localizations are available). With its broad spectral coverage and both imaging and spectral modes available, RIMAS will be a powerful tool for rapid (within minutes) photometric and spectroscopic follow-up of *Swift* GRBs.

Design Details: A drawing of the optical and mechanical layout of RIMAS is shown in Figure 2. Before entering the main dewar, the beam enters a front module, an attachment to the dewar operating at ≈ 60 K under vacuum. The attachment contains field-limiting slits, which can be placed at the focus of the telescope for use with the dispersive elements. Slits of various sizes or an open slot for photometry can be selected by rotating a slit wheel. The surface of each slit is a mirror that reflects light into a slit-imaging camera (256 x 256 pixel, $80''$ diameter IR detector) to help observers center light from their source through the slit. The slit-wheel will have a pick-off mirror for the future installation of MOHSIS, a fiber-Bragg grating (FBG) atmospheric hydroxyl (OH) emission line suppressor. Behind the slit-wheel, there is a filter wheel for program-specific specialty filters.

All of the optics are kept cold ($T \approx 60$ K) to reduce thermal background, which is crucial at the long end of the instrument bandpass in K-band. The beam is separated into two optical arms by a dichroic beamsplitter. The first arm is for the Y- and J-bands (0.97–1.07 and 1.17–1.33 μm, respectively), and the second is for the H- and K-bands (1.49-1.78 and 2.03–2.37 μm, respectively). Each arm has a filter wheel that holds broadband photometric filters as well as low ($R \approx 25$) and high ($R \approx 4500$) spectral resolving power diffractive elements. The wheels allow the observer or automation software to switch between instrument modes within seconds. The light of each arm will be focused onto a Teledyne HAWAII-2RG (H2RG) detector.

[1] `http://www.lowell.edu/techSpecs/LMI/LMI.html`

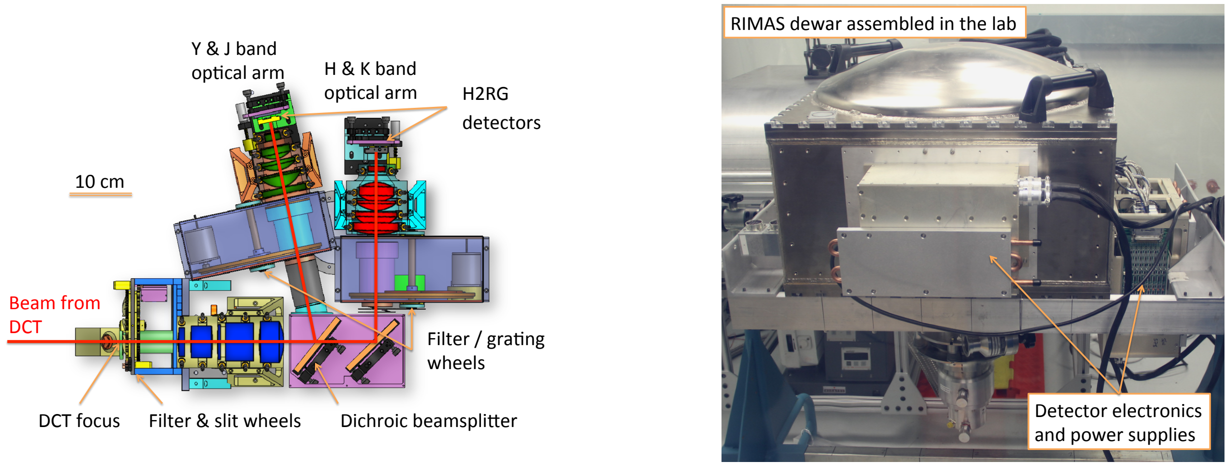

Figure 2: *Left panel*: The layout of the optical and mechanical elements used in RIMAS. Light from the DCT first passes through the filter and slit wheels in the front module, is collimated and continues until focused by the "YJ-band" (0.9–1.4 μm) or "HK-band" (1.4–2.4 μm) camera. *Right panel*: A photo of RIMAS in the lab at Goddard Space Flight Center.

High-resolution spectroscopy will be achieved for each optical arm by using multiple, cross-dispersed orders of transmission gratings (Figure 3). RIMAS can change modes in 10s of seconds.

Expected Performance: Based on the pre-commissioning calculations of the system throughput, we estimate the following 10σ limiting magnitudes (AB) will be achieved in a 400 s integration in imaging mode for a point source obtained under good conditions: $Y > 22.1$, $J > 22.0$, $H > 21.2$, $K > 20.7$. Limiting magnitudes for a 1 hr integration using the low-resolution ($R \approx 25$) spectral mode are very similar to these imaging limits. For comparison, these values are $\gtrsim 1.5$ mag deeper in all filters than those typically achieved by e.g., GROND, in their prompt follow-up GCNs. Predictions of the overall fractional efficiency for RIMAS's imaging modes are plotted in Figure 3.

Similarly, we estimate we will be able to achieve a SNR per resolution element of 10 in a 1 hr exposure in the high-resolution echelle mode with the $0.6''$ slit for sources with the following (AB) magnitudes: $Y = 18.1$, $J = 17.6$, $H = 16.1$, and $K = 15.2$. After correcting for comparable SNRs and slit widths, these sensitivities are comparable to analogous instruments on similar-sized telescopes, e.g., TripleSpec on the Palomar 200 inch telescope, and TripleSpec on the 3.5 m ARC telescope.

We expect that RIMAS will be able to begin spectroscopy within 5 minutes of a bright GRB trigger. On an observing run to help with the *telescope* commissioning in February 2014, we observed GRB140215A with LMI and were able to get on source within 3 minutes of the *Swift* trigger manually. We expect this response time will be further reduced with automation software. The planned RIMAS software will take short exposure images and automatically decide whether it should continue with longer exposure images or if the source is bright enough to switch to either low- or high- resolution spectroscopy.

Project Status: The RIMAS instrument is currently in the process of assembly at GSFC (Figure 2). The dewar has passed all cryo-mechanical tests in the lab. We have acquired both of the H2RG detectors (for the Y/J arm and the H/K arm), as well as the detector drive and image acquisition electronics (Leach-based). We are currently characterizing the detectors in RIMAS's dewar.

All optics excluding the gratings and two out of the four broadband filters have been received and characterized. The guide camera has been aligned at room temperature while science optics remain to be AR coated before aligned in their mounts at room temperature. We are working with Lawrence Livermore National Laboratory (LLNL) to produce the required dispersive elements (gratings).

The mechanical structure is partially built (e.g., the internal optical bench and the detector mounts). We have half of the opto-mechanical components and the other half are currently being fabricated. We expect all of the necessary hardware tasks will have been completed by the commencement of Cycle 11 (1 April 2015), and the instrument will be shipped for installation on the DCT around this time.

Remaining Tasks: While the hardware design, acquisition, and integration is underway and largely funded, our

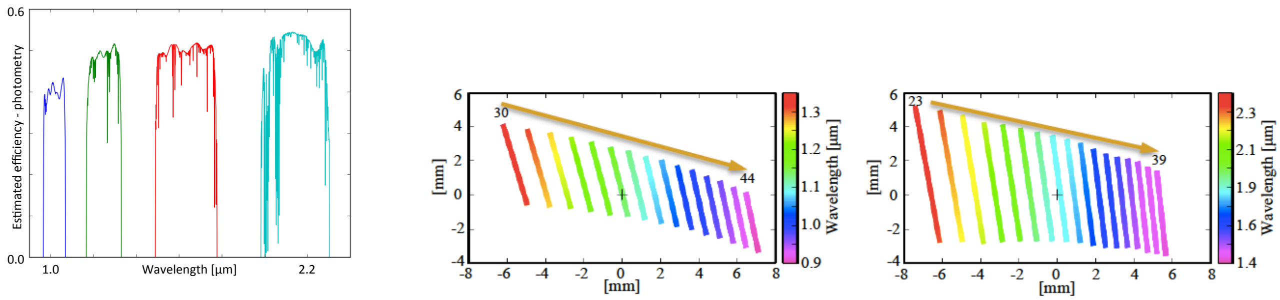

Figure 3: Left: Estimated instrument photometric efficiency including atmospheric absorption, losses for each optical element and detector response. Right: Model spectra produced by the Y/J grism (left) and H/K grism (right). The cross-dispersed echelle configuration allows for simultaneous coverage from 0.9–2.4 μm with a resolution of $R \approx 4500$. The numbers and arrows above the spectra mark the grism diffraction orders.

experience with RATIR, P60, etc. indicate that our software needs will be significant. In particular, the bulk of our requested funding is dedicated to two major software efforts:

- We request funding for a professional programmer to handle the low-level (e.g., C++ level) software to control the instrument and interface with the DCT. This effort would include routine operations (e.g., selecting instrument configuration, writing out resulting exposures with appropriate FITS header keywords), as well as the development of a rapid-response mode suitable for automated multi-color follow-up and (as appropriate) spectroscopy of *Swift* GRBs.

- We also request funding for a graduate student to develop higher-level (e.g., python) analysis tools to promptly reduce both the imaging and spectroscopic outputs into fully processed data products (i.e., a pipeline) and automation software to allow RIMAS to quickly decide between its operating modes.

A more detailed budget is provided in the Budget Narrative section at the end of this proposal.

3. Justification of Requested Observing Time, Feasibility and Visibility

We are not requesting any additional *Swift* observations for this program. Instead we estimate the number of GRBs we will be able to observe with RIMAS when it is fully operational; how many we will detect (photometrically) and how many we will follow up spectroscopically (e.g. redshifts).

Based on our past experience with robotic follow-up of *Swift* GRBs (P60, RATIR), we anticipate that ≈ 10 GRBs will be promptly ($\Delta t < 1$ hr) observable to the DCT over the course of Cycle 11. An additional 20–30 events will be observable within 1 d of the burst trigger time.

We can estimate our detection efficiency using the sample of *Swift* GRBs with prompt ($\Delta t < 1$ d) observations by the GROND instrument on the MPI/ESO 2.2 m telescope on La Silla (Chile)[12]. Using their simultaneous 7-color imager, these authors report detecting $\approx 90\%$ of GRBs observed within 1 hr, and $\approx 60\%$ of GRBs observed within 1 d. Given that RIMAS on the 4.3 m DCT is expected to be ≈ 1.5 mag more sensitive in the NIR than GROND, these recovery fractions represent conservative lower limits for what we can expect with RIMAS. We therefore expect to detect (via broadband imaging) $\gtrsim 30$ GRB afterglows.

Nearly all of the events we detect via broadband imaging will be sufficiently bright to obtain low-resolution ($R \approx 25$) spectra. This will allow crude spectroscopic estimates for all events at $z \gtrsim 6.5$ via the detection of a Lyα break, and upper redshift limits (from the lack of a Ly-break) for *all events detected by RIMAS*. Based on the relative rate of high-redshift GRBs in the *Swift* sample[11,12], we expect to detect ≈ 1 GRB at $z \gtrsim 7$, and several events at $z \gtrsim 5$ each year.

It is difficult to reliably predict how many events will be suitably bright for high-resolution spectroscopy with RIMAS. For simplicity, we can compare with known high-redshifts events. GRB 090423[8] was observed at $K = 18.0$ mag at $\Delta t = 40$ min, and $J = 19.2$ mag at $\Delta t = 80$ min. Both filters are sufficiently bright that we could obtain modest SNR (≈ 5 per resolution element) with a 1 hr integration with RIMAS. Similarly, GRB 050904[18] was observed with $J = 18.3$ mag at $\Delta t = 3$ hr, and $K = 18.6$ mag as late as $\Delta t = 8$ hr after the burst trigger. If observed promptly, it is nearly certain that GRB 050904 could have been well-detected by RIMAS.

Our collaboration has observed GRB afterglows at visible wavelengths during 4 separate, one week runs (classically scheduled) using LMI on DCT. To date we have observed 12 GRB afterglows with 9 accompanying GCN circulars (Table 1), demonstrating the quality of the site and telescope. Additionally, we were able to begin observing GRB 140215A 2.7 minutes post-bust without automation software. We expect that we will further improve this response time once RIMAS has been commissioned and automated.

Swift name	**Detected?**	**GCN circulars**
GRB140129A	No	
GRB140209A	No	
GRB140206A	Yes	15835
GRB140215A	Yes	15838, 15850
GRB140311A	No	
GRB140318A	Yes	15989
GRB140606A	Yes	16367, 16377
GRB140606B	No	
GRB140610A	No	
GRB140614B	No	
GRB140903A	Yes	16769, 16785
GRB140907A	Yes	16802, 16818

Table 1: GRB observations with DCT-LMI

4. Justification of Duplication

N/A.

5. Report on Previous Swift and Related Programs

This is our second time proposing for *Swift* funding for RIMAS – our Cycle 10 proposal was highly rated but not funded. In previous cycles, several members of our collaboration received *Swift* GI funding for the construction and commissioning of RATIR, a simultaneous 4-band optical and NIR imager mounted on the 1.5 m Johnson telescope on Sierra San Pedro Martir in Baja California. RATIR now routinely observes *Swift* GRB afterglows, publishing $>$ 100 GCNs over the past 3 years, with over a dozen refereed journal publications and many others in the preparation stage.

6. References

References

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7. Budget Narrative

Costs are summarized in the table below and are fully loaded, i.e., salaries include fringe benefits and all necessary items include appropriate institutional overheads. The components of the cost are:

- 6 months of effort (0.5 FTE) from a professional software engineer to provide the low-level tools to control the instrument and interface with the DCT. We plan to hire this individual as a (short-term) contractor at GSFC, for an estimated total cost of $60k.
- 6 months of effort (0.5 FTE) from 1–2 University of Maryland graduate students to develop a data reduction pipeline for RIMAS. In order to make intelligent decisions regarding the appropriate follow-up strategy for *Swift* GRBs in real-time (i.e., broadband imaging or spectroscopy), the pipeline will need to be capable of prompt reductions (at least with preliminary calibrations). A more precise and robust pipeline for science-quality reductions, of obvious utility for the entire RIMAS user base, can be executed in a more leisurely manner (but will also be developed by these students). We estimate a total cost for this effort of $25k.
- 1 month of effort (0.1 FTE) for co-I Kutyrev to coordinate the instrument commissioning, including the installation of the hardware on the DCT, as well as supervising the professional programmer and graduate student(s) in software development. The total cost of his effort will be $10k.
- 1 month of effort (0.1 FTE) for co-I Norris, to assist in the theoretical interpretation of early RIMAS results, in particular relating $x_{\mathrm{H\,I}}$ measurements from RIMAS to previously observed QSOs as well as in the broader context of reionization physics.
- $10k for travel, including multiple trips for team members (Kutyrev, Cenko, and graduate students) to Flagstaff, AZ (location of the DCT) for instrument installation and/or upgrades, as well as for co-I Norris to visit GSFC to work with the team on interpreting the observations.
- $5k for publishing our results, including journal pages charges (e.g., ApJ), as well as for 1–2 team members (preferably graduate students) to travel to scientific conferences to present our results.

The total request cost thus comes to $120k, with a total FTE request of 1.2.

Projected Costs

Professional Software Development	60k
Graduate Student Pipeline	25k
Kutyrev Oversight	10k
Norris Theoretical Interpretation	10k
Travel (DCT Commissioning, Upgrades)	10k
Publications (Page Charges, Conference)	5k
Total Cost	**120k**