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 2014. RIMAS can operate in three modes: 1) Simultaneous 2-band imaging; 2) High-throughput, $R \sim 25$ NIR spectroscopy; 3) High-resolution ($R \approx 4500$), cross-dispersed echelle spectroscopy providing simultaneous coverage from 0.9–2.4 μm. Unlike other large aperture facilities that are classically scheduled, RIMAS will be continuously available for ToO observations through a pick-off mirror. By the end of cycle 10, we intend for RIMAS to 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]) seemed to imply at least a modest neutral H fraction ($x_{\mathrm{H\,I}}$) at this time. However, observations of the cosmic microwave background (CMB[2]) indicate a significantly larger characteristic redshift for reionization to occur: $z_{\mathrm{reion}} \approx 10$. 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. But 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 $x_{\mathrm{H\,I}}$ 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 $x_{\mathrm{H\,I}}$ measurements[7]; 3) Because they result from the core-collapse of a single massive star, GRBs are not biased towards the most massive halos[7].

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 (Figure 1) enabled for the first time a strict upper limit on the neutral H fraction of $x_{\mathrm{H\,I}} < 0.11$ from the lack of a Lyα red damping wing[13].

Despite these remarkable successes, as a community we still lack the ultimate prize: meaningful constraints on $x_{\mathrm{H\,I}}$ 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;[14,11,12]) and true high-redshift GRBs, let alone measure $x_{\mathrm{H\,I}}$ 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 *continuously available* on the 4.3 m Discovery Channel Telescope (AZ) in early 2014.

B) Immediate Objective:

Our principle objective is quite straightforward: by the end of Cycle 10, 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

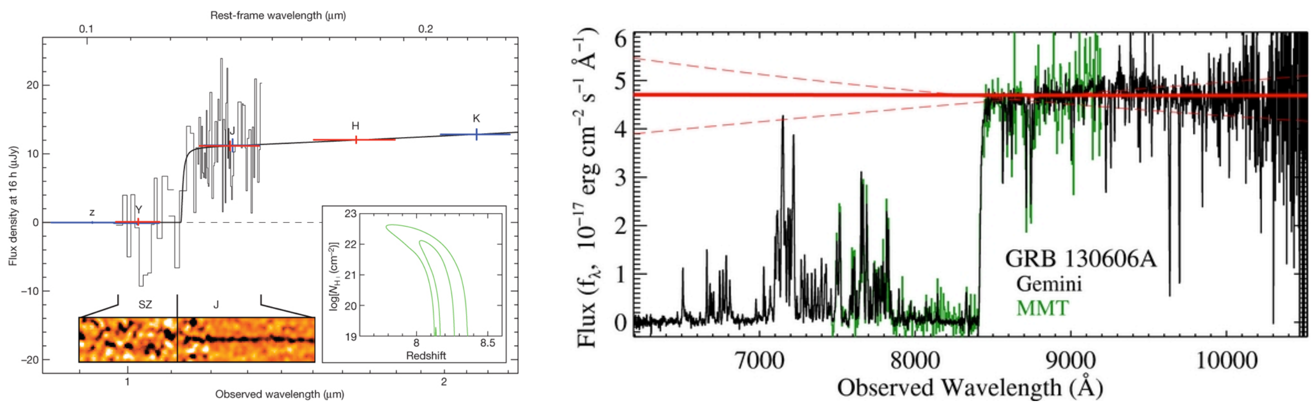

Figure 1: *Left panel*: NIR spectrum of the afterglow of the $z = 8.2$ GRB 090423[8], obtained with ISAAC on the VLT at full 16 hr after the burst trigger time. While the sharp break in the spectrum (consistent with that obtained from broadband photometry) indicates a redshift of $z \approx 8.2$, the low SNR precludes meaningful constraints on $x_{\rm H\,I}$. *Right panel*: Optical spectra of the $z = 5.913$ GRB 130606A[13]. The sharp drop in flux blueward of ~ 8300 Å is due to absorption from neutral H in the host galaxy and intervening IGM. Modeling the red wing of the Lyα absorption enabled the first constraints on $x_{\rm H\,I}$ comparable to what has been obtained from QSOs at $z \approx 6$. However, thus far, no high SNR spectra of a GRB afterglow has been obtained at a redshift directly probing the epoch of reionization ($z \gtrsim 7$).

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 the DCT "instrument cube", where a pick-off mirror will allow users to switch between multiple instruments with an overhead of only seconds.

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$'$. With its broad spectral coverage and both imaging and spectral modes available, RIMAS will be a powerful tool for both 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 can be selected by rotating a wheel. Although the final widths remain to be decided, it is likely that widths of 0.6$''$, 1$''$, and 2$''$ will be included. The surface surrounding each slit is tilted and covered in a flat mirror in order to reflect the surrounding area into "slit-imaging" optics. These optics will image fields surrounding the slits on a small (256×256 pixels, 80$''$ diameter) legacy indium antimonide (InSb) Spitzer IRCAM detector to help observers center light from their source onto the slits. The slit-wheel will also have an open slot for imaging modes and a pick-off mirror for the future installation of MOHSIS, a fiber-Bragg grating (FBG) atmospheric hydroxyl (OH) emission line suppressor. Near the slit-wheel, there is a second wheel that has eight positions for program-specific specialty filters. These filters are contained in the front dewar attachment so they may be replaced easily without disassembling the main dewar.

All of the optics are kept cold ($T \approx 60$ K) within a double-dome dewar. These cooled optics reduce thermal background, which is crucial at the long end of the instruments wavelengths in K-band. As light enters the dewar (after passing through the front dewar attachment), the beam is collimated by a lens assembly before being separated by a dichroic into two optical arms. 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 mum, respectively). Near the pupil of each arm is a wheel that holds broadband photometric filters as well as low ($R \approx 25$) and moderate ($R \approx 4500$) spectral resolving power diffractive elements. Rotating these wheels allows the observer to select the operational mode of the instrument. After passing through either a filter or diffractive element, the light of each arm will be focused by camera optics onto a Teledyne HAWAII-2RG (H2RG) detector.

Moderate resolution spectroscopy will be achieved for each optical arm by using multiple, cross-dispersed or-

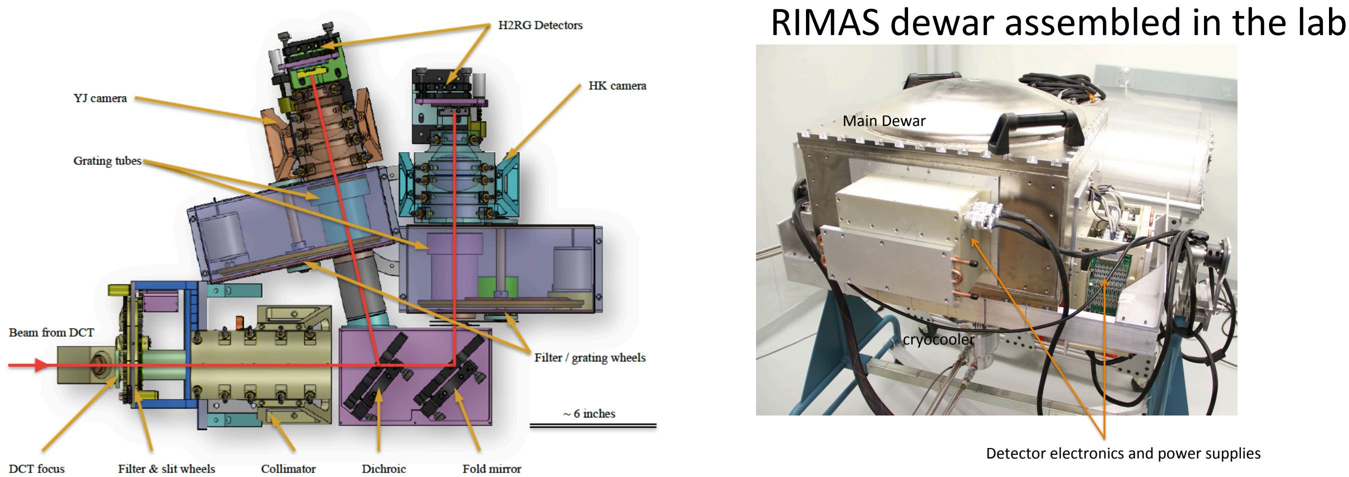

Figure 2: *Left panel*: The layout of the optical and mechanical elements used in RIMAS. Light from the DCT first passes through the filter and slit wheels in the front module, is collimated and continues until focused by the "YJ-band" (0.9–1.4 μm) or "HK-band" (1.4–2.4 μm) camera. *Right panel*: A photo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

ders of blazed grating prisms (grisms; Figure 3). The grisms will be produced at Lawrence Livermore National Laboratory (LLNL) where similar optics have been ruled for projects including the James Web Space Telescope. All of the wheels used in the design will be rotated by stepper motors, allowing the setup to be changed in $\lesssim 15$ s.

Expected Performance: Based on the pre-fabrication 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.

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.

Project Status: The RIMAS instrument is currently in the process of assembly at GSFC (Figure 2). The dewar has been acquired and is undergoing a battery of cryo-mechanical tests in the lab at the moment. 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 also currently testing the acquisition software for the detectors.

The optical design has been completed, and necessary lenses have been ordered and fabricated (we are currently in the process of acceptance). We have already obtained two of the four necessary broadband filters, and are working with LLNL to produce the required dispersive elements (gratings and grisms).

The mechanical structure is partially built (e.g., the internal optical bench and the detector mounts), and we are in the process of finalizing the design and construction of the opto-mechanical components. We expect all of the necessary hardware tasks will have been completed by the commencement of Cycle 10 (1 April 2014), 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 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.

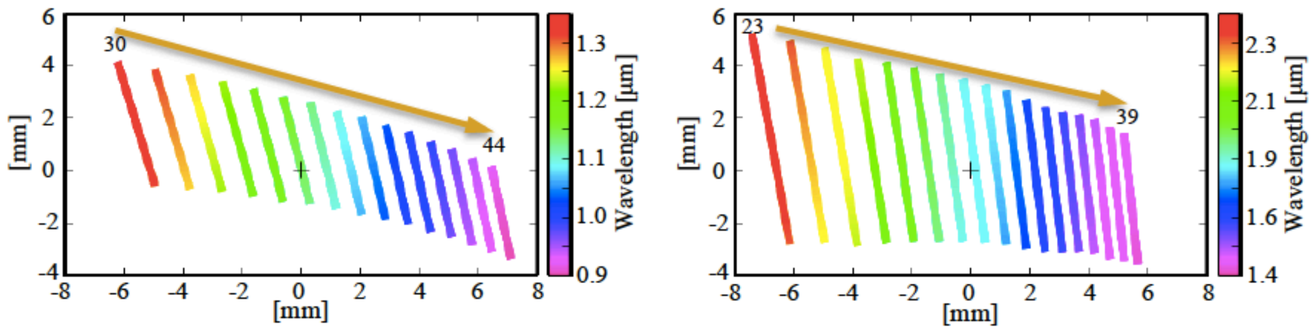

Figure 3: Model spectra produced by the Y/J grism (left) and H/K grism (right). The cross-dispersed echelle configuration allows for simultaneous coverage from 0.9–2.4 μm with a resolution of $R \approx 4500$. The numbers and arrows above the spectra mark the grism diffraction orders.

- 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).

A more detailed budget is provided in the Cost Overview 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 attempt to estimate here the number of GRBs we will be able to observe with RIMAS when it is fully operational, and how many of these we will be able to observe, detect (photometrically), and obtain spectroscopic redshifts for.

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 10. 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 with prompt ($\Delta t < 1$ d) with 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 recovering $\approx 90\%$ 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 extremely 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[15] 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 likely GRB 050904 could have been well-detected by RIMAS.

4. Report on Previous Swift and Related Programs

This is our first request specifically for funding for RIMAS. 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 54 GCNs in 2013 alone, with multiple publications to refereed journals in the final stages of preparation.

5. NASA Strategic Objectives

Our study of GRBs is directly in line with NASA objective 3D.1, "understanding the origin and destiny of the Universe, phenomenon near black holes, and the nature of gravity.", as well as 3D.2, "understand how the first stars and galaxies formed, and how they changed over time into the objects recognized in the present universe."

6. Applicant's Most Relevant Publications

Capone, J. I. et al., 2013, Proc. of SPIE, 8863, 8863-14: *The development and analysis of cryogenic optical systems for the rapid infrared imager/spectrometer*
Butler, N. R. et al., 2012, Proc. of SPIE, 8446, 8446-10: *First Light with RATIR: an Automated 6-band Optical/NIR Imaging Camera*
Cenko, S. B. et al., 2006, PASP, 118, 1396: *The Automated Palomar 60 Inch Telescope*
Cenko, S. B. et al., 2009, ApJ, 693, 1484: *Dark Bursts in the Swift Era: The P60-Swift Early Optical Afterglow Catalog*
Perley, D. A. et al., 2009, AJ, 138, 1690: *The Host Galaxies of Swift Dark Gamma-Ray Bursts: Observational Constraints on Highly Obscured and Very High-Redshift GRBs*
Tanvir, N. R. et al., 2009, Nature, 461, 1264: *A gamma-ray burst at a redshift of 8.2*
Haislip, J. B. et al., 2006, Nature, 440, 181: *A photometric redshift of* $z = 6.39 \pm 0.12$ *for GRB 050904*
Morgan, A. N. et al., 2013, MNRAS submitted (astro-ph/1305.1928): *Evidence for Dust Destruction from the Early-time Colour Change of GRB 120119A*
Perley, D. A. et al., 2013, ApJ submitted (astro-ph/1301.5903): *A Population of Massive, Luminous Galaxies Hosting Heavily Dust-Obscured Gamma-Ray Bursts: Implications for the Use of GRBs as Tracers of Cosmic Star Formation*
Svensson, K. M. et al., 2012, MNRAS, 421, 25: *The dark GRB 080207 in an extremely red host and the implications for gamma-ray bursts in highly obscured environments*
Perley, D. A. et al., 2011, AJ, 141, 36: *Monster in the Dark: The Ultraluminous GRB 080607 and Its Dusty Environment*
Cenko, S. B. et al., 2010, AJ, 140, 224: *Unveiling the Origin of GRB 090709A: Lack of Periodicity in a Reddened Cosmological Long-Duration Gamma-Ray Burst*

7. References

References

1. Becker, R. H. *et al.* *AJ*, **122**, 2850–2857, December 2001.
2. Hinshaw, G. *et al.* *ApJS*, **208**, 19, October 2013.
3. Lamb, D. Q. and Reichart, D. E. *ApJ*, **536**, 1–18, June 2000.
4. Racusin, J. L. *et al.* *Nature*, **455**, 183–188, September 2008.
5. Bloom, J. S. *et al.* *ApJ*, **691**, 723–737, January 2009.
6. Kann, D. A., Masetti, N., and Klose, S. *AJ*, **133**, 1187–1192, March 2007.
7. McQuinn, M. *et al.* *MNRAS*, **388**, 1101–1110, August 2008.
8. Tanvir, N. R. *et al.* *Nature*, **461**, 1254–1257, October 2009.
9. Salvaterra, R. *et al.* *Nature*, **461**, 1258–1260, October 2009.
10. Cucchiara, A. *et al.* *ApJ*, **736**, 7, July 2011.
11. Perley, D. A. *et al.* *AJ*, **138**, 1690–1708, December 2009.
12. Greiner, J. *et al.* *A&A*, **526**, A30, February 2011.
13. Chornock, R. *et al.* *ApJ*, **774**, 26, September 2013.
14. Cenko, S. B. *et al.* *ApJ*, **693**, 1484–1493, March 2009.
15. Haislip, J. B. *et al.* *Nature*, **440**, 181–183, March 2006.

8. Cost Overview

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:

- 4 months of effort (0.3 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 $40k.
- 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 PI Kutyrev to oversee the effort, 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 $100k, with a total FTE request of 1.0.

Projected Costs

Professional Software Development	40k
Graduate Student Pipeline	25k
Kutyrev Oversight	10k
Norris Theoretical Interpretation	10k
Travel (DCT Commissioning, Upgrades)	10k
Publications (Page Charges, Conference)	5k
Total Cost	**100k**