Sounding Rocket Instrument Development at UAHuntsville / NASA MSFC

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ABSTRACT

We present an overview of solar sounding rocket instruments developed jointly by NASA Marshall Space Flight Center and the University of Alabama in Huntsville. The High Resolution Coronal Imager (Hi-C) is an EUV (19.3 nm) imaging telescope which was flown successfully in July 2012. The Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) is a Lyman Alpha (121.6 nm) spectropolarimeter developed jointly with the National Astronomical Observatory of Japan and scheduled for launch in 2015. The Marshall Grazing Incidence X-ray Spectrograph is a soft X-ray (0.5-1.2 keV) stigmatic spectrograph designed to achieve 5 arcsecond spatial resolution along the slit.

Keywords: solar, corona, stigmatic, spectrograph, x-ray

1. INTRODUCTION

One of the key goals in solar physics is to understand the energy and mass flow into and through the solar atmosphere; "determining how the Sun's magnetism creates its hot, dynamic atmosphere" is identified as a science challenge by the 2012 Decadel Panel. The solar atmosphere consists of the cool, dense chromosphere (~ 20 kK) and hotter, more tenuous corona (≥ 1 MK). Numerous theories have been introduced to explain the million-degree corona since its discovery in the 1930s, most of which hinge on the dynamics and structures of magnetic fields in the solar atmosphere.

Vector magnetic field measurements in the solar photosphere are now routine, thanks to the advances in ground based instruments such as the Marshall Space Flight Center (MSFC) vector magnetograph[1] and the Advanced Stokes Polarimeter,[2] and now the Heliospheric and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory (SDO).[3] However, these observations target the photosphere where the dynamics is dominated by gas pressure (i.e. β, the ratio of the gas pressure to the magnetic pressure, is > 1). At higher levels in the atmosphere, $\beta < 1$, which means the magnetic field controls the structure and dynamics of the solar atmosphere,[4] and rapid changes in its structure can produce energetic events. However, observations of the magnetic field at these higher levels have proven to be difficult, placing a serious limitation on our understanding of the physical processes actually occurring there.

X-ray and EUV imaging telescopes provide valuable information on the morphology of the solar atmopsphere. Nevertheless, these observations have had limited spatial resolution. While the $0.5''$ resolution images from the Transition Region and Coronal Explorer (TRACE[5]) and the SDO Atmospheric Imaging Assembly (AIA[6]) have revolutionized our understanding of the structure of the transition region and corona, there is ample evidence to suggest the existence of

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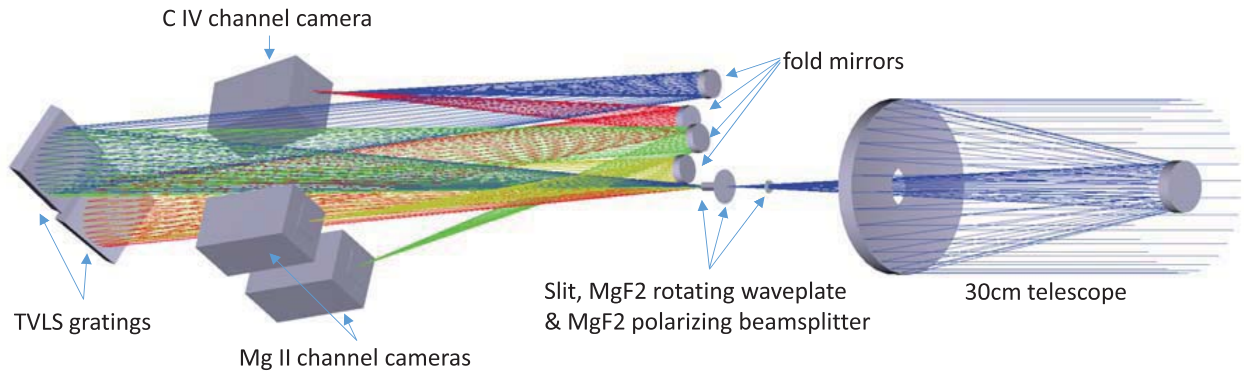


Figure 1. Optical configuration of the SUMI. The incident UV light is focused by a Cassegrain telescope, modulated by the rotating waveplate, then sampled by the slit and split into two two beams with a polarizing beamsplitter. Each beam is directed onto separate TVLS gratings. The four resulting beams (two polarizations $\times$ two passbands) are reflected by individual fold mirrors and focused onto three cameras; one 512×512 pixel camera for each Mg II beam, and one 1024×256 camera imaging both C IV beams. The slitjaw system is not shown.

unresolved detail. For example, in a study of twenty loops observed with AIA and the Extreme-ultraviolet Imaging Spectrometer (EIS) on *Hinode* have found that observed loops at $\sim$ 1.5 MK can be explained as one to several strands with widths of 450 – 3000 km.[7] Analysis of the footpoints of higher temperature ($>$ 2 MK) active region core loops, or "moss," observed with EIS have determined the filling factor of $\approx$ 15%, which equates to a scale size of roughly 300 km.[8] Additionally, some chromospheric features observed in the high-resolution ($0.054''$ pixel^{-1}) Solar Optical Telescope (SOT) on Hinode appear similar to coronal features.

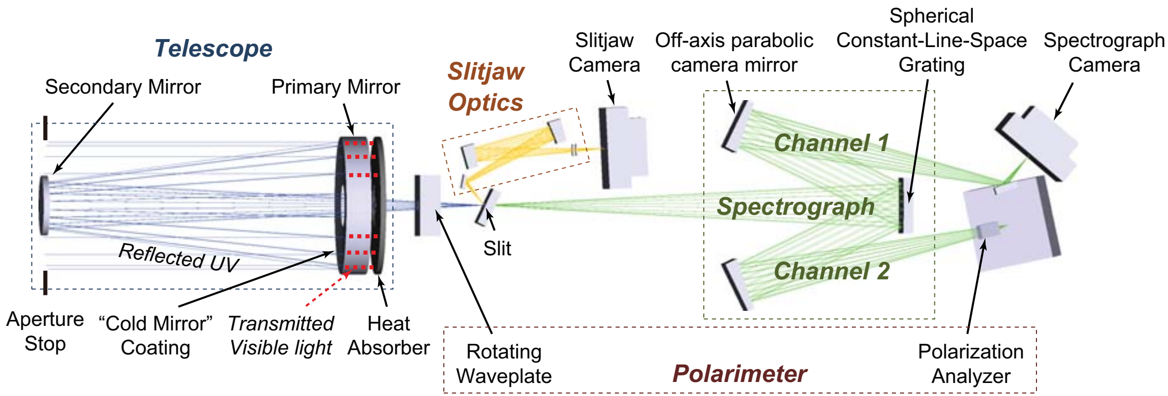
The Huntsville solar physics group aims to address these issues through development and use of new and improved space-based instruments. These goals have driven us to develop techniques ranging from ultraviolet (UV) spectropolarimetry to high-resolution extre ultraviolet (EUV) imaging and grazing-incidence X-ray optics, as well as development of sounding rocket avionics. Our development efforts are characterized into 3 paths: (1) Direct magnetic field measurements in the solar atmosphere, (2) High-resolution coronal imaging, and (3) coronal diagnostics. On path 1, we have successfully developed and flown the Solar Ultraviolet Magnetograph Instrument in 2010 and 2012, and a second instrument, the Chromospheric Lyman Alpha SpectroPolarimeter (CLASP), has been selected for flight in 2015. On path 2, the High Resolution Coronal Imager (Hi-C) flew successfully in 2012, and has been proposed for reflight. On path 3, the Marshall Grazing Incidence SpectroPolarimeter (MaGIXS) is under development and has been proposed for flight.

2. DIRECT MAGNETIC FIELD MEASUREMENTS

2.1 Solar Ultraviolet Magnetograph Instrument (SUMI)

The Solar Ultraviolet Magnetograph Investigation (SUMI)[9] was designed to measure the polarization in the ultraviolet lines of C IV (154.82 nm & 155.08 nm) and Mg II (279.64 nm & 280.35 nm) which are formed in the transition region and upper chromosphere. SUMI consists of a Cassegrain telescope, a dual-beam dual-passband spectropolarimeter, and a slitjaw system (Figure 1). The telescope utilizes a "cold mirror" design which uses multilayer mirrors to focus the target UV passbands onto the focal plane while rejecting the visible light. The spectropolarimeter consists of a rotating MgF_2 waveplate,[10] a MgF_2 double Wollaston prism (polarizing beamsplitter), a pair of toroidal varied line space gratings, and 3 CCD cameras: one each for the Mg II beams and one observing both beams of the C IV passband.

SUMI was first launched in July 2010. While it met its stated success criteria, problems with the mechanical stability of the telescope secondary mirror and an electrical problem with the waveplate rotation mechanism resulted in poor quality data that could not be deconvluted into Stokes profiles. With these problems addressed, SUMI was launched for the second time in July 2012. Again all stated success criteria were met. Analysis is currently in preparation for publication.



Telescope	
Type	Cassegrain
Aperture	ø277.4 mm
Eff. Focal Length	2614 mm (F/9.42)
Primary Mirror	ø290 mm (clear aperture), F/3.54
Secondary Mirror	ø119.4 mm
Visible Light Rejection	"Cold Mirror" coating on primary mirror

Slit	
Slit Width	18.4 µm (1.45 arcsec)
Slit Length	5.1 mm (400 arcsec)

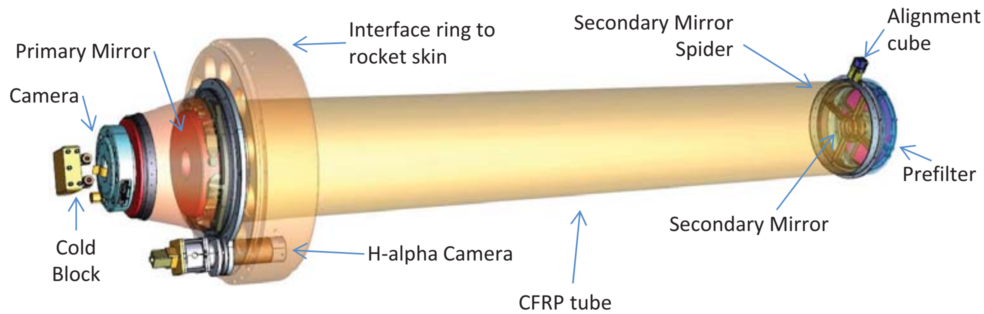
Slitjaw Imaging System	
Wavelength	Lyα (band-pass filter)
Optics	- Fold mirror with multilayer coating - Off-axis parabola x 2 - Lyα filter x 2
Detector	512 x 512 CCD, 13µm pixel
Plate Scale	1.03 arcsec / pixel
Resolution	2.9 arcsec (spot RMS diameter)
FOV	527 arcsec x 527 arcsec

Polarimeter	
Measurements	Stokes I, Q, U
Capability	Simultaneous measurement of orthogonal polarizations
Optics	- Rotating 1/2 waveplate - Polarization analyzer x 2

Spectrograph	
Spectrograph Type	Inverse Wadsworth mounting
Grating Type	Spherical constant-line-space with 3600 mm^{-1} groove density
Grating Size	ø106 mm (clear aperture)
Wavelength	Optimized for Lyα (121.567 nm)
Camera Mirror	Off-axis parabola
Resolution	0.01 nm (spectral; RMS diameter) 2.8 arcsec (spatial; RMS diameter)
Magnification	0.73

Spectrograph Cameras	
Detector	512 x 512 CCD, 13µm pixel
Exposure Time	0.3 sec (nominal)
Plate Scale	0.0048 nm / pixel (spectral) 1.40 arcsec / pixel (spatial)
Field of View	121.567±0.61 nm (spectral) 400 arcsec (along slit)

Figure 2. Optical layout and baseline specifications of CLASP.



Telescope		Camera	
Type	Ritchey-Chrétien	Detector	Back-illuminated CCD
Aperture	220 mm	Pixel size	12 µm
Effective focal length	23.9 m (F/109)	Format	3880 × 4096
Primary Mirror	220 mm F/9.1	FOV	6.66 x 7.03 arcmin
Coatings	19.3 nm multilayer	Plate scale	0.103" / pixel

Figure 3. Hi-C instrument layout and specifications. This section is pumped down to ¡1 torr before launch to allow the CCD to be cooled to $-60°$C, and to eliminate acoustic shock which can damage the thin metal filters. Not shown are the rocket skins with its associated hardware (vacuum pumping port and LN2 feedthrough), and an avionics section separated from the telescope section with a vacuum bulkhead.

2.2 Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP)

In the solar chromosphere and transition region, Zeeman effect in UV lines is only expected to be observable in the strong magnetic fields of active region cores. The Hanle effect has been proposed as a method for detecting and measuring weaker magnetic fields, e.g. in the quiet Sun. The Hanle effect is just the modification of the linear polarization produced by scattering processes due to the presence of a magnetic field. This effect is sensitive to weaker magnetic fields. Moreover, Hanle effect is not cancelled by fields that are tangled at spatial scales too small to be resolved. In the 121.567 nm Lyman α line, the Hanle effect is predicted to be sensitive to magnetic field strength between 10 G and 250 G. For an on-disk near-limb observation, the Hanle effect is expected to manifest as a reduction in Stokes Q/I (perpendicular to the limb) of order 0.2%, and an increase in Stokes U/I of order 0.2%, depending on field angle.[11]

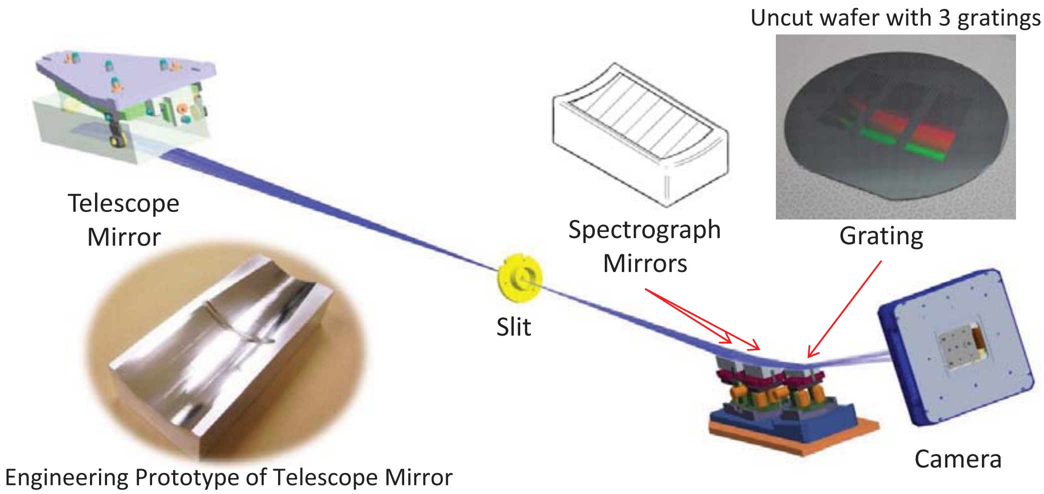
Like SUMI, CLASP[12] consists of a Cassegrain telescope with a polarization modulator (MgF_2 rotating waveplate) feeding a dual-beam spectropolarimeter (Figure 2). Because birefringent prisms are inefficient at this wavelength, the diffraction grating is used as a beamsplitter. A multilayer reflective polarizer is used on each output beam as a polarization analyzer.

CLASP is currently in the final stages of design and initial stages of fabrication. It is scheduled for flight in summer of 2015.

3. HIGH RESOLUTION IMAGING

3.1 High Resolution Coronal Imager (Hi-C)

Hi-C aims to better understand the structure and dynamics of the solar atmosphere through high resolution EUV imaging. The experiment represents an evolutionalry step that draws on the heritage of the SDO AIA telescopes. By increasing the focal length of the primary mirror, the inter-optic spacing between the primary and secondary mirrors, and the magnification of the secondary mirror, a plate scale of $0.103''$/pixel is achieved, which represents an order of magnitude improvement in terms of aerial resolution. To achieve an optical performance to match the pixel scale, the mirror figure and alignment accuracy are improved.[13] Unlike AIA, Hi-C uses a single 19.3 nm passband, which results in higher throughput and also a higher cadence of 5.5 s in full frame readout mode. The CCD is a flight spare from SDO with a 4096×4096 pixels.



Telescope	
Type	Wolter Type-I Sector
Mirror Substrate	Zerodur
Graze Angle	1.0°
Sector Size	34°
Aperture (Geometric Area)	96 mm^2
Effective Focal Length	1090 mm

Spectrograph Specifications	
Passband	6.0 — 23.0 Å (0.5 – 2.0 keV)
Plate scale	11 mÅ / pixel (wavelength) 2.8 arcsec / pixel (spatial)

Spectrograph Mirrors	
Type	Parabolic sector mirrors
Graze Angle	2.0°
Size	45 x 25 mm (tangential x saggital)
Focal Length	597 mm

Grating	
Type	Planar Varied Line Space
Size	64 x 25 mm (tangential x sagittal)
Material	Silicon wafer
Ruling	2146 – 2709 lines/mm

Figure 4. Optical layout and baseline specifications of MaGIXS.

The first flight of Hi-C on July 11, 2012 was a full success, with 36 full-resolution images obtained at a 5.5 s cadence as well as 86 images of a 1024×1024 ROI at a cadence of 1.4 s. A reflight is proposed, with an upgrade of telescope to a dual-bandpass design.

4. CORONAL DIAGNOSTICS

4.1 Marshall Grazing Incidence X-ray Spectrograph (MaGIXS)

MaGIXS is designed to provide the first instantaneous, spatially resolved X-ray spectra of the solar corona. There are two main scientific objective for MaGIXS. The first is to determine the nature of active region heating events through temperature diagnostics of high-temperature corona. EUV spectrographs currently opearating (e.g. Hinode/EIS) provide accurate measurement of the differential emission measure (DEM) up to $LogT = 6.8$ range.[14] However, determination of DEM up to higher temperatures require observation of higher temperature lines. A grazing-incidence spectrograph designed to cover a wavelength range of 10–23Å is capable of measuring coronal DEM up to $LogT = 7.3$, providing a strong constraint on the heating timescale and mechanism of the corona. The second science objective is to measure the variation of elemental abundance in solar active region structures. The same 10–23Å wavelength coverage allows observation of emission lines from a number of elements, including Mg, Ne, Fe, and O. This allows MaGIXS to measure how elemental abundance varies across the active region as a function of first ionizaiton potential (FIP).

The optical design and baseline optical parameters for the MaGIXS sounding rocket experiment[15] are shown in Figure 4. The spectrograph consists of 3 elements: a matched pair of parabolic mirrors that act as a collimator and a reimaging mirror, and a planar varied line space grating. The 2-mirror design corrects for coma and achieves a significantly wider field of view than a single elliptical mirror. The placement of the grating in the converging beam is necessitated by the wavelength range requirement; placing the grating in the collimated beam would simplify the grating design, but the wavelength range would be severely limited by the off-axis aberration of the reimaging mirror. The specrograph mirrors are made of Zerodur, and first polished as a complete continous cylinder before they are cut into sectors. The diffraction grating is planar, with a very large variation in line spacing. A lithographically ruled silicon grating has been chosen, as this fabrication method allows for arbitrary ruling patterns but only on a flat silicon wafer.

The telescope is a sector (segment) of a Wolter Type-1 design, with the beam angle (F number) matched to the spectrograph. The sector design allows the mirror to be measured face-on using an interferometer. However, because of the large deviation from a cylinder, a cylindrical null was judged to be insufficient. A set of computer generated holograms have been procured to match the presription of the MaGIXS telescope.

MaGIXS has been proposed as a sounding rocket experiment with a 2016 launch. A significant amount of devleopment work on MaGIXS have already been completed. MSFC has fabricated a set of flight-like spectrograph mirrors. Several flight-candidate gratings have been procured from Lightsmyth Technologies. These mirrors and grating have been installed in the MaGIXS concept model, a laboratory device which allow the alignment of these optics inside a vacuum chamber. The concept model is currently being used to develop the alignment process. In addition, UAH Center for Applied Optics has started fabrication of a flight candidate telescope mirror. The Zerodur blank has been "grolished" using a Zeeko polishing machine, and awaiting final polishing using the CGSs for metrology.

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