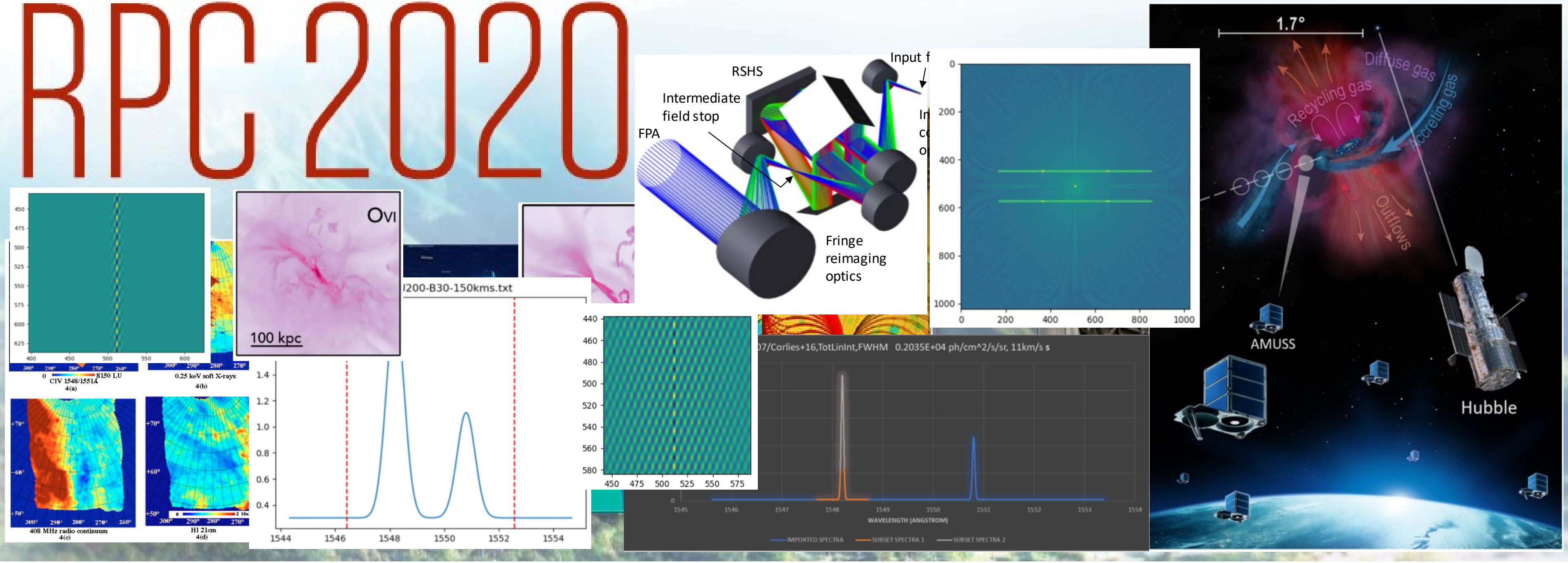
RPC 2020



Virtual Research Presentation Conference

From Astrospheres to the Circum-Galactic Medium: Studying Faint, Extended Structures in the UV using a Novel Spectroscopic Instrument

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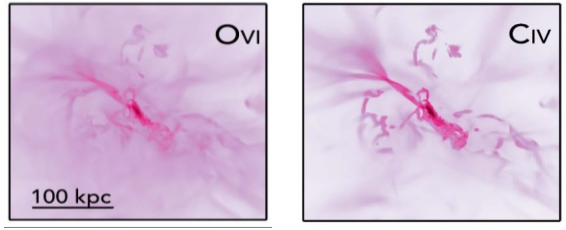
Co-Is: Sona Hosseini (3224)
Program: Topic

Assigned Presentation # R19109

Introduction



FUV emission-lines from the CGM of a galaxy (simulation: Corlies+Schiminovich 2016)

Abstract: Our overall goal is aimed at understanding the Cosmic Order (i.e., the formation and evolution of galaxies), the cycling of matter through the interstellar medium (ISM) in our Galaxy, and the life-cycles of stars that evolve in a Hubble time, which requires observing the UV emission-line properties of faint and diffuse astrophysical environments. We present the design of a novel spectroscopic instrument (a Spatial Heterodyne Spectrometer or SHS), that can collect photons from large angular regions on the sky (~arcmin to a deg) using a small aperture telescope for a SmallSat/CubeSat mission (AMUSS) and deliver R~100,000 spectroscopy of UV lines. Our main objectives during this 2-year program were to develop (i) a model that computes the spectrum of Lyman-Werner H2 lines (near 1610 A) from shells of gas (representing astrospheres around dying stars) excited by hot electrons, (ii) estimate the intensity in diagnostic lines such as CIV 1550A that can probe the ISM of our Galaxy and the circumgalactic medium (CGM) around nearby galaxies (using previous observations and/or numerical simulations, together with the photoionization code for astrophysical plasmas, CLOUDY) and (iii) use the derived intensities in a signal-to-noise instrument performance model that drives the AMUSS mission design.

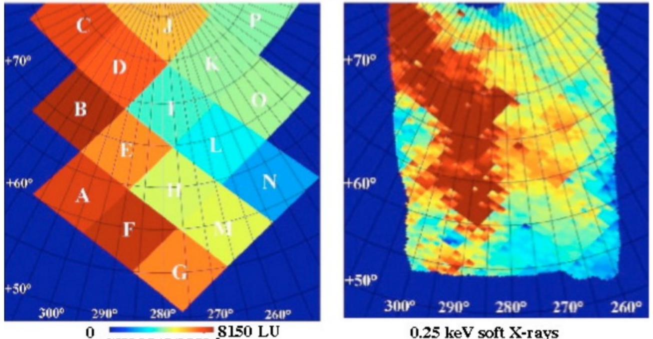
Problem Description

a) **Context:** Observations of the low-surface-brightness Universe hold the key to major astrophysical topics of current interest (see IAU Symposium 355, http://research.iac.es/congreso/iaus355//, July 8-12, 2019). These include, e.g., the formation and evolution of galaxies, which requires probing the CircumGalactic Medium (CGM) around a representative sample of galaxies, the cycling of matter through the interstellar medium (ISM) in our Galaxy, and the life-cycles of stars that evolve in a Hubble time. Determining the physical properties (density, temperature and kinematic structure) of the faintly-emitting warm/hot gas that pervades these astrophysical environments requires spectroscopic observations of diagnostic UV emission lines. We present model estimates of the line-intensities from our targets and the design of a novel spectroscopic instrument (a Spatial Heterodyne Spectrometer or SHS), that can collect photons from large angular regions (~arcmin to a deg) that sample our targets, in order to obtain (R~100,000) spectroscopy of UV lines. Our design uses a small aperture telescope, that together with our instruemnt, can be flown on a SmallSat/CubeSat mission (AMUSS).

b) **SOA:** Conventional high spectral-resolution spectrometers (which use narrow-slits) are large in size and have a small field-of-view and therefore cannot collect enough photons to obtain spectra with adequate signal-to-noise. SHS is a miniature high spectral resolution spectrometer that has the capability to observe large, faint, extended targets coupled to small aperture telescopes that fits into SmallSats.

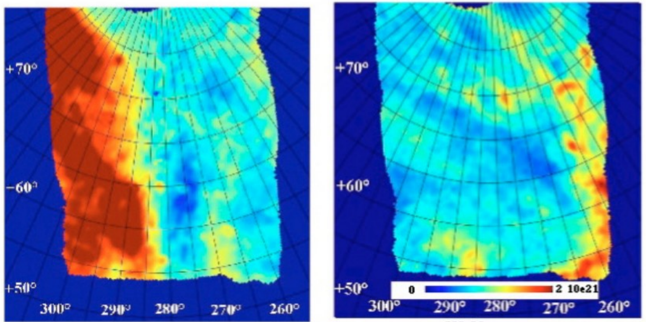
c) **Relevance to NASA and JPL:** Development of the SHS design and instrument performance model at UV wavelengths for SmallSat/CubeSat missions, supports NASA's goal of carrying out low-cost missions with fast turn-around which can be used to address ma oblems in astrophysics, and will enable JPL to take the lead in proposing such space missions.

Methodology/ Results: ISM -- Simulations and Expected Radiance for FUV Lines



CIV 1548/1551Å
4(a)

0.25 keV soft X-rays
4(b)



408 MHz radio continuum
4(c)

HI 21cm
4(d)

The surface-brightness of the CIV line for the North Galactic Pole region, observed with the SPEAR onboard Korean STSAT-1, compared to X-ray (10^6 K gas), radio (10^4 K gas), and HI (neutral gas) emission (from Welsh+07)

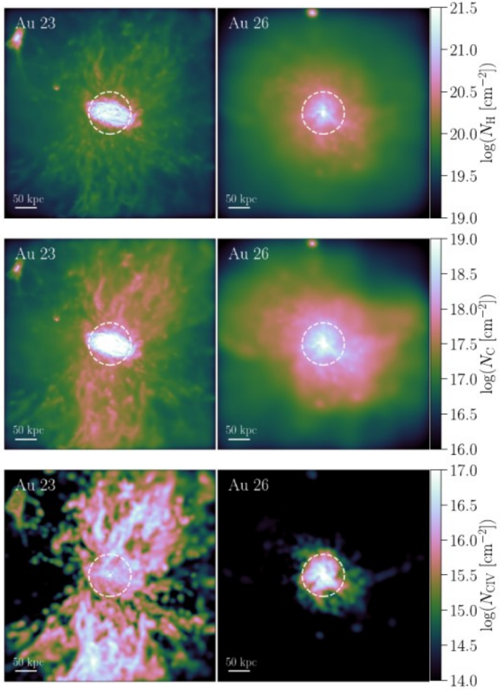
Important diagnostic cooling lines for ionized ISM at $10^{4.5\text{-}5.7}$ K are C IV (1550A), O VI (1032A), Si IV (1394A)

- The low resolution 8 x 8 deg^2 in previous survey is inadequate (see CIV emission, tracing $10^{4.5\text{-}5}$ K gas in figure)
- The presence of very significant structure at smaller scales is expected based on absorption-line observations with the FUSE mission.

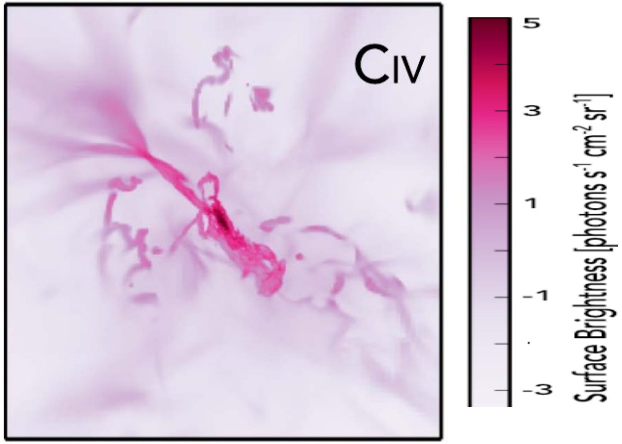
Surface-brightness of the best lines
C IV ~ 1e8 to 5e8 ph / s / m^2 / sr /A
O VI ~ 7e8 to 2e9 ph / s / m^2 / sr /A
Si IV ~ 1e8 to 3e8 ph / s / m^2 / sr /A

AMUSS will provide *velocity-resolved* maps at ~0.2 x 0.2 deg^2 resolution

• **Methodology/Results**: CGM -- Simulations and Expected Radiance for FUV Lines



Two CGM simulations (A23, A26) showing the column densities of hydrogen, C and CIV - the very different structure between the two simulations is due to differences in star-formation rate, disk fraction, and AGB activity (from Hani+2019)



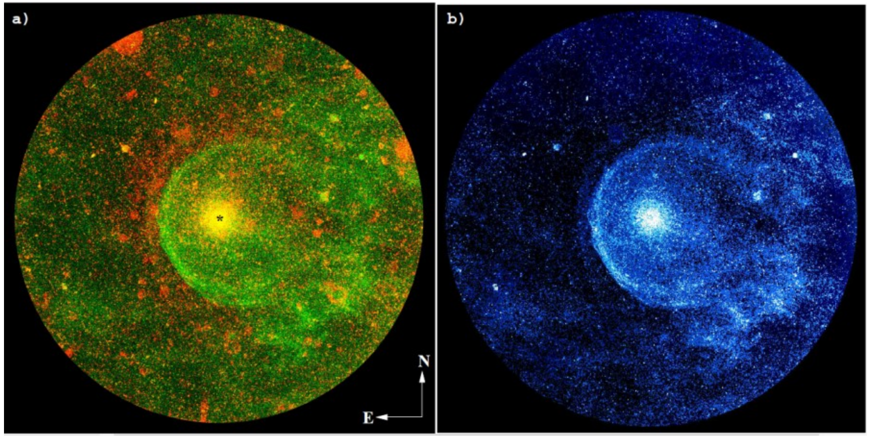
CIV 1550 A emission from a CGM simulation assuming Milky Way properties (from Corlies+Schiminovich 2016). OVI looks very similar

- **surface-brightness of C IV and O VI lines in the bright/medium-bright regions is**

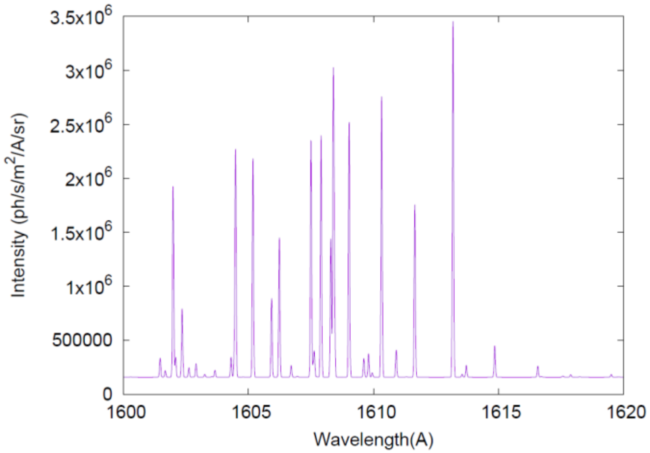
~1e6 to 1e8 ph / s / m^2 / sr /A

- **AMUSS will provide *velocity-resolved* maps at <0.3 x 0.3 deg^2 resolution**

Methodology/ Results: Astrospheres -- Simulations & Expected Radiance for FUV Lines



(a) Composite [NUV (*red*) & FUV (*green*)] GALEX image of the dying star IRC+10216 (the circular field-of-view (FOV) has a diameter of 61.6’×61.6’); the NUV(FUV) image is displayed using a linear (square-root) stretch. The location of the central star is indicated by a ⋆ (b) The FUV image (same FOV as in a), which is less affected by bright star residuals and artifacts displayed using a linear stretch (in false color), to clearly show the detailed structure of the astropause and its tail (from Sahai & Chronopoulos 2010). **Most or all of the mass ejection which leads to the star's death is enclosed within the astropause, and spectral-line observations of the faint FUV emission are needed to constrain the mass of the ejecta.**



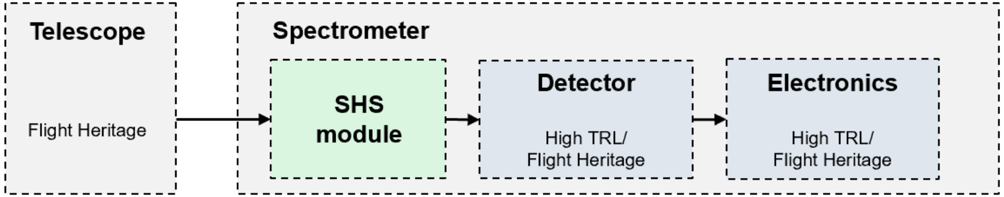
Model spectrum of H2 Lyman-Werner band lines, believed to be excited by hot electrons in astropauses and responsible for their FUV broad-band emission. The spectrum is scaled to an intensity that is 1/100 times fainter than the average value for IRC+10216, extracted from a 3.8 arcmin diameter aperture located on the astropause

AMUSS, coupled to a 15 cm telescope, in a field-widened desgin, can detect the above spectrum with a S/N~3 in ~4 hr with an angular resolution of about 0.6 x 1.2 arcmin^2 and spectral resolution of 1.2 km/s

Reference Instrument Parameters and Technique

In choosing the instrument technique and parameters for measuring the CGM and ISM we considered the assumptions below:

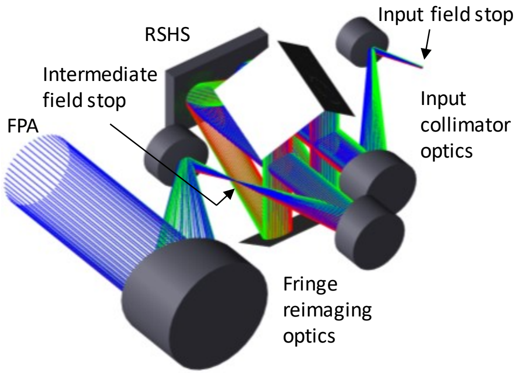
1. **Technique:** The instrument used here is based on Spatial Heterodyne Spectrometer (SHS) technique. SHS obtains high spectral resolution measurements over a narrow targeted spectra with no moving parts.
2. **System block diagram:** The spectrometer consists of three modules. Light collected by the telescope enters the SHS module. The array detector records the interference fringe.



3. **Reference mission, SmallSats:** We require dedicated SmallSat to comply with long exposure times to satisfy the measurement requirements. Our reference payload includes an SHS instrument observing the targeted bandpass for ISM and CGM spectral lines. SHS instruments can be build ultra-compact with no moving parts.
4. **Telescope aperture size:** the telescope changes the projection of SHS FOV on the sky and it does not change the SHS spectrometer Etendue. The reference telescope size used here is different for ISM and CGM to satisfy the spatial resolution reequipment in our STM. In future mission configuration, we can use a telescope mask or develop two small telescopes for two ultra-compact SHS where one observe ISM and the other observes CGM targets.

Spatial Heterodyne Spectrometry (SHS) technique

We developed an instrument concept model for the telescope and the spectrometer (with the all-reflective SHS design) with a set of parameters for spectral bandwidth, spectral resolution, field of view, étendue, detector array size and instrument efficiency. The simulation reported here does not include the effects if the detector nonlinearities, effects due to detector flat fielding, grating and mirror surface scattering, mechanical design vignetting. The optical design concept reference here (picture below) has not been optimized for form factor and efficiency.

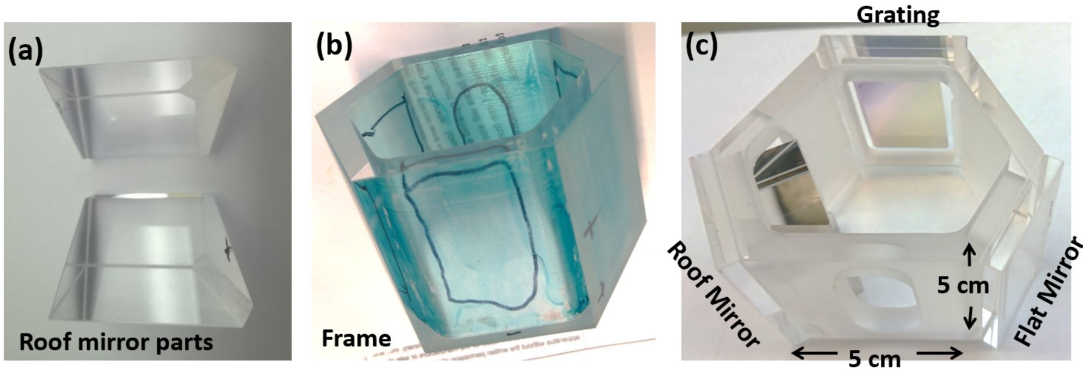


Assumptions:

Telescope: 2 reflections
SHS: 3 reflections and two diffractions
Spectrometer: 5 reflections

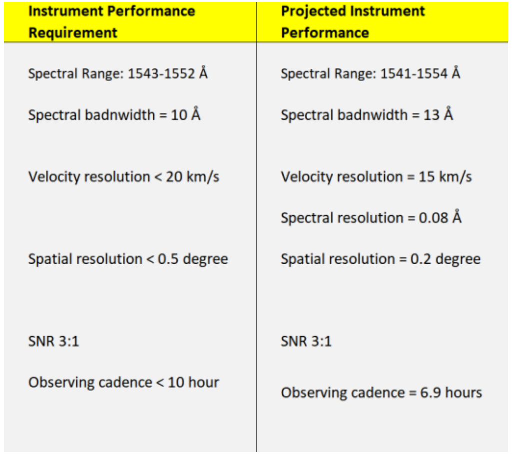
Mirror reflectivity: ~%98
Grating first diffraction: ~%35
Grating second diffraction: ~%20
Sensor QE > %80

Extra material (no audio)

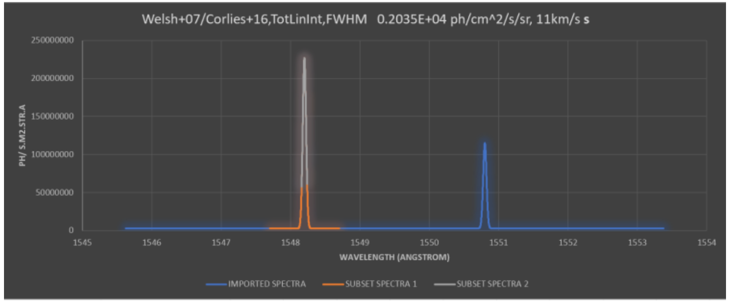


Here we show the picture of the breadboard hardware in our lab. The SHS module in here is ~155 grams. **(a)** The flat mirror, roof mirror and the grating are separately fabricated and coated. **(b)** The datum block's outer hexagon is machined from a solid block of Fused Silica. The inner hollow area is removed, then the port holes are removed using Ultra-Sonic CNC machining. A small chamfer is added to some of the edges to prevent chipping. **(c)** The optical elements are contact-bonded to the datum block, effectively creating one solid block of glass as shown here for our TRL 3 OH-SHS in 3073 Å.

Results: ISM Performance vs. requirement



Instrument Performance Requirement	**Projected Instrument Performance**
Spectral Range: 1543-1552 Å	Spectral Range: 1541-1554 Å
Spectral badnwidth = 10 Å	Spectral badnwidth = 13 Å
Velocity resolution < 20 km/s	Velocity resolution = 15 km/s
	Spectral resolution = 0.08 Å
Spatial resolution < 0.5 degree	Spatial resolution = 0.2 degree
SNR 3:1	SNR 3:1
Observing cadence < 10 hour	Observing cadence = 6.9 hours

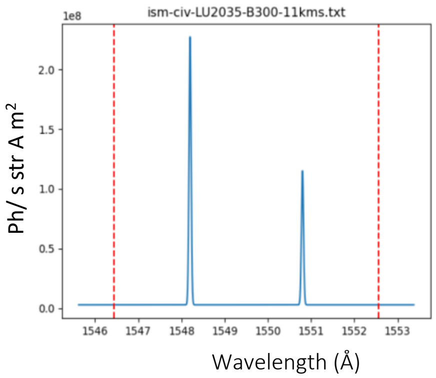


SHS design	Cyclical SHS design with no field widening
Beamwidth on the grating (mm)	20
Grating groove density (grooves/mm)	4320
Bandpass (A)	13
Etendue [A.Omega] (m2 str)	4.3E-09
Telescope diameter (m)	0.02
FOV on sky along the d. plane (degree)	0.2
Dark current (e/read)	6
Read noise current (e-/pixel)	2.9E-05
Detector Q.E. at wavelength of interest	0.8
Pixel size (um)	13
det.pix.num (N) across d.plane	3000
Transmission of SHS	8.47%
Transmission of Spectrometer and Telescope	4.59%
Transmission of the System (telescope + spectrometer + detector)	3.68%
Total Exposure time (sec)	24740.17
Effective Resolving power	19415.73
Effective Spectral resolution (A)	0.08
Effective Velocity resolution (km/s)	15.44
Intensity in wvl.of.interest (ph/s.m2.str)	1.22E+07
Intensity over the entire bandpass (ph/s.m2.str)	5.27E+07
SNR of wavelength of interest	3

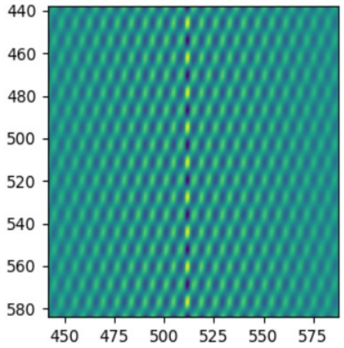
Results: ISM simulated data

We have developed an SHS instrument performance model to simulate the data taken from our spectral profile given a set of reference SHS instrument parameters.

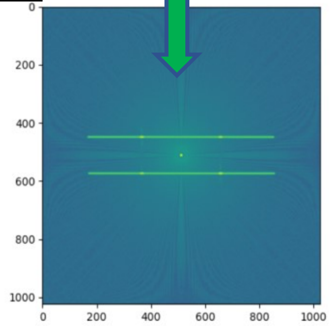
The figures show the simulated interference pattern obtained from the ISM spectral profile given our reference SHS instrument parameters presented in the previous slide. The simulated fringe pattern is then reduced with the 2D FFT process algorithm to obtain the reduced spectral profile.



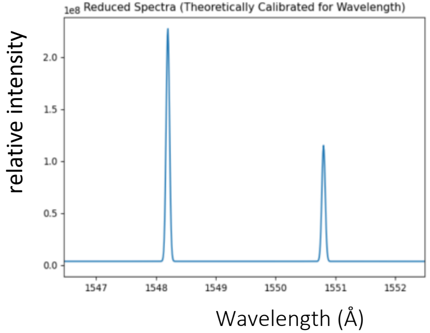
Simulated spectra



Simulated measurement

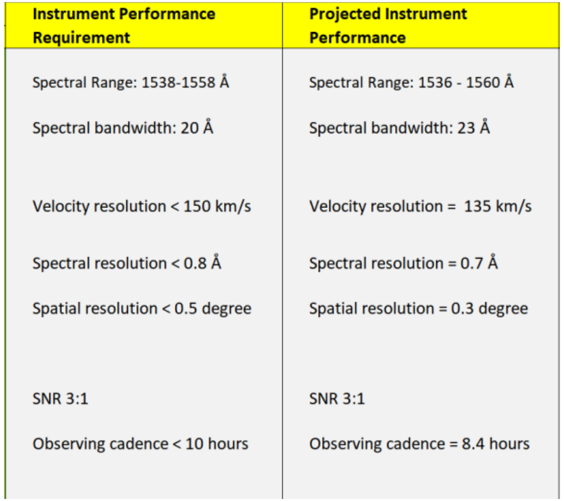


2D FFT reduction from the simulated data (shown in log scale)

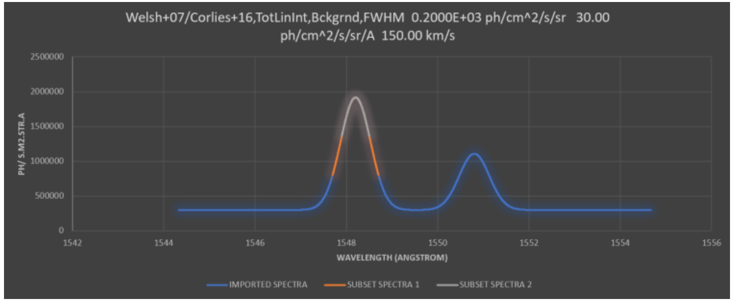


Reduced spectra from the simulated data

Results: CGM Performance vs. requirement



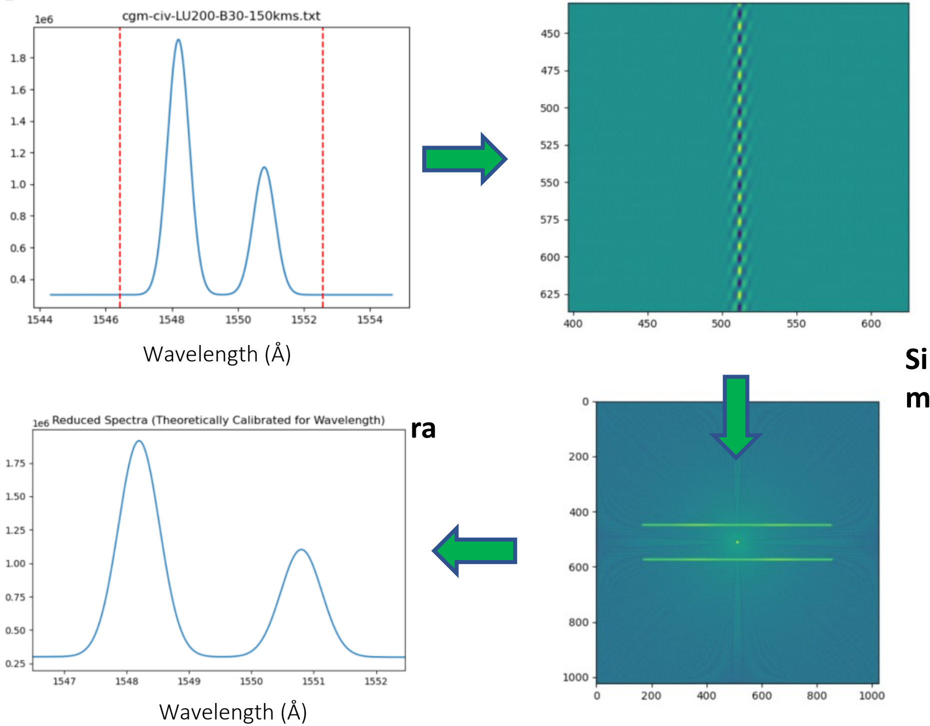
Instrument Performance Requirement	Projected Instrument Performance
Spectral Range: 1538-1558 Å	Spectral Range: 1536 - 1560 Å
Spectral bandwidth: 20 Å	Spectral bandwidth: 23 Å
Velocity resolution < 150 km/s	Velocity resolution = 135 km/s
Spectral resolution < 0.8 Å	Spectral resolution = 0.7 Å
Spatial resolution < 0.5 degree	Spatial resolution = 0.3 degree
SNR 3:1	SNR 3:1
Observing cadence < 10 hours	Observing cadence = 8.4 hours



SHS design	Cyclical SHS design with field widening
Beamwidth on the grating (mm)	20.0
Grating groove density (grooves/mm)	4320.0
Bandpass range start (A)	1536.9
Bandpass range end (A)	1560.056
Bandpass (A)	23.11
Etendue [A.Omega] (m2 str)	5.32E-08
Telescope diameter (m)	3.00E-02
FOV on sky along the d. plane (degree)	0.32
Dark current (e/pixel)	3.86E-67
Read noise current (e-/read)	6.00
Detector Q.E. at wavelength of interest	0.8
Pixel size (um)	1.30E+01
det.pix.num (N) across d.plane	5.12E+03
Transmission of SHS	8.47%
Transmission of Spectrometer and Telescope	4.32%
Transmission of the System (telescope + spectrometer + detector)	3.4%
Total Exposure time (sec)	30455.76
Effective Resolving power	2598.50
Effective Spectral resolution (A)	0.60
Effective Velocity resolution (km/s)	115.3
Intensity in wvl.of.interest in one spectral bin (ph/s.m2.str)	1.14E+06
Intensity over the entire bandpass (ph/s.m2.str)	6.92E+06
SNR of wavelength of interest	3

Results: CGM simulated data

The figures show the simulated interference pattern obtained from the ISM spectral profile given our reference SHS instrument parameters presented in the previous slide. The simulated fringe pattern is then reduced with the 2D FFT process algorithm to obtain the reduced spectral profile.



Simulated measurements

Reduced spectra from the simulated data

2D FFT reduction from the simulated data (shown in log scale)

Next Steps

Science next steps include:

- The galactic ISM emission is a contaminant while observing the CGM. Thus the targets for CGM observations have to be chosen very carefully, in order to minimize the ISM contamination, e.g., select external galaxies that are located at high galactic latitudes , and/or are adequately Doppler-shifted from the ISM emission, so that the latter can be excuded from the bandpass.

Technical next steps include:

- Design the SHS instrument optical and mechanical structure with optical ray tracing programs to simulate the instrument parameters, the stray light and instrumental error sources to verify the instrument parameters and the system efficiency and for the sensitivity and error propagation retrievals.
- Investigate the use of photon-counting detectors to reduce the read-noise budget.
- Internal investment to develop the instrument hardware to TRL 4 so we can propose flight hardware maturation through future proposal calls. The individual instrument parts are at higher TRL but because we lack experimental measurements at the wavelengths of our spectral lines, we assessed the overall TRL to be 3.

Mission formulation next steps include:

- Develop a Verification Validation Uncertainty Quantification (VVUQ) model to construct a well-formulated STM for the flight instrument.

Publications

[A] *"Faint But Not Forgotten: Stellar Astrospheres*", Sahai, R., 2020, The Realm of the Low-Surface-Brightness Universe, IAU Symp. 355 (proc), eds. D. Valls-Gabaud, I. Trujillo & S. Okamoto (in press)

[B] *"AMUSS – Astrophysics Miniaturized UV Spatial Spectrometer for spectroscopic studies of diffuse astrophysical objects",* Hosseini, S. & Sahai, R. 2020, The Realm of the Low-Surface-Brightness Universe, IAU Symp. 355, (proc), eds. D. Valls-Gabaud, I. Trujillo & S. Okamoto (in press)

[C] *"From Astrospheres to the Interstellar Medium and the Circum-Galactic Medium: Spectroscopic Observations of Faint UV Emission Lines with a Novel Spatial Heterodyne Spectrometer in Space*", 2020, Sahai, R. & Hosseini, S. (in prep.)