Спектральные исследования газа в туманностях (спектрограф SING): общие задачи и предварительный оптический расчет

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Ультрафиолетовый спектральный диапазон (ближний УФ, 180–300 нм; дальний УФ, 115–180 нм) крайне востребован астрофизиками. Успешные космические проекты, такие как IUE, HST, GALEX, ASTROCAT/UVIT и другие, дали ученым совершенно новые данные для астрофизических исследований. Прямые УФ-изображения неба позволяют проследить морфологию протяженных объектов (планетарных туманностей, остатков сверхновых и т.д.), но эти данные дают очень ограниченную информацию о понимании физических условий (температура, плотность, поле излучения). Спектроскопические наблюдения позволяют изучать локальные физические условия, но обычно только в одной точке протяженной туманности. Спектроскопия, основанная на наблюдениях с помощью спектрографа с длинной щелью, позволяет объединить два этих метода. Для изучения динамики и эволюции протяженных объектов мы предлагаем такой инструмент — SING (Spectroscopic Investigation of Nebular Gas, спектроскопические исследования газа туманностей). Мы планируем установить его на борту китайской космической станции. В данной статье представлены общие задачи и предварительный оптический расчет прибора SING.

Ключевые слова: спектроскопия, газовые туманности, оптический расчет

Spectroscopic Investigation of Nebular Gas (SING): general objectives and preliminary optical layout

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The ultraviolet spectral subdiapasons, both near UV (180–300 nm) and far UV (115–180 nm), are highly requested by astrophysicists. The successful space missions like IUE, HST, GALEX and others provided scientists with absolutely new data for astrophysical studies. Direct UV images of the sky allow tracking the morphology of extended objects (planetary nebulae, supernova remnants etc), but these data provide very limited information about understanding the physical conditions (temperature, density, radiation field). Spectroscopic observations make it possible to study local physical conditions, but usually only at one point in an extended nebula. Spectroscopy that is based on long-slit spectrograph observations allow to combine these both. To study dynamics and evolution of extended objects we propose such an instrument SING (Spectroscopic Investigation of Nebular Gas). We plan to install it onboard the upcoming Chinese Modular Space Station (CSS). Here we describe general objectives and preliminary optical layout of the SING.

Keywords: spectroscopy, gas nebulae, optical layout

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1. Introduction

One of the most exciting parts of the astrophysical spectrum is the ultraviolet (we are talking here about 120–300 nm wavelengths), where there are a number of important atomic and molecular lines. Hot gas in the halo emits C IV (154.8/155.0 nm), and many other lines as do other shocked regions — most notably, supernova remnants (SNR). The Lyman and Werner bands of H_2 track cold gas, the dominant phase of the ISM. Unfortunately, the requirement for space-qualified detectors has limited the observations to a very few spacecraft (IUE, STIS, COS, SPEAR), none of which have had the unique combination of spectral and spatial resolution, sensitivity to diffuse sources, and mission lifetime required to probe the physics of nebulae or the ISM. The success of the GALEX and ASTROSAT/UVIT telescopes have given us a new view of the UV sky with unprecedented detail on extended objects such as planetary nebulae [1] and supernova remnants [2]. However, imaging observations excel at tracing the morphology but not at understanding the astrophysics; i.e., the physical conditions, temperatures, densities, and radiation fields. Spectroscopic observations provide a wealth of diagnostics on the local physical conditions but, so far, have been limited to a single location in the extended nebula.

We propose to build an imaging spectrograph (SING) to track emission lines over the entire spatial extent of a nebula; key to understanding its dynamics and evolution.

2. Objectives

Our primary science objective is to study the physical conditions in extended regions of the sky. These encompass many phases of the ISM, from the hot gas in supernova remnants (SNR) to the warm gas in planetary nebulae

Table 1: List of atomic/molecular emission lines in SING range.

Lines (nm)	
OIII]	232.1, 233.1
He II	230.7, 238.6, 242.2, 251.2, 273.4
CIII	229.7
NeIV]	242.3
CII	232.6, 283.6
OII]	247.0
Graphite	217.5
NII]	214.0
CIII]	190.9
SiIII]	189.2
NIII	175.0
AlII	167.1
CIV	154.8, 155.1
SiII]	153.3
H_2	143.0–162.0

to cold gas in molecular clouds including emission lines from hot gas (C IV 154.8/155.0 nm), warm gas (N III 175.0 nm) and the Lyman and Werner bands of molecular hydrogen from cold gas. One of the major puzzles for cosmologists today is understanding why the abundances of primordial isotopes at high redshifts is much higher than that at low redshifts. It is likely that much of the missing baryons are in hot gas in and around clusters (WHIM), in the cosmic web and in the circumgalactic medium (CGM) around galaxies. Such gas has been detected in specific lines through absorption line spectroscopy of quasars [3] but would be better tracked through emission lines in the WHIM [4]. A long-slit spectrograph such as SING will detect the emission from C IV and other lines and will track the hot gas, both Galactic and extragalactic, from the interior of galaxy clusters to the cosmic web. Such an instrument also works well for observations of outflows (and inflows) from AGNs. A large fraction of AGN have strong outflows of ionized gas, which pushes back the infalling gas, thus limiting gas accretion onto the AGN in a process called negative AGN feedback. There may also be positive AGN feedback, due to gas flowing back onto the AGN and forming stars [5], with a comprehensive survey required to understand when the two are important. Positioning our long slit across such a galaxy (or cluster of galaxies) would allow us to map the velocities at different radii.

Focusing on our own Galaxy, the blast waves from supernova explosions can last for thousands of years, expanding into and interacting with the surrounding circumstellar and/or interstellar medium (ISM). Supernova shocks pass through the various phases of the ISM, heating and energizing the gas. UV studies of supernova remnants have been heavily slanted toward studies of individual bright optically-emitting filaments, such as those in Cygnus Loop or the Vela Nebula. These two objects are nearby, bright, and relatively free of reddening, and hence have been the primary targets of UV studies from IUE, HUT, and FUSE (e.g. [6]). However, these have been individual pointings, many of which would be required to observe the entire nebula. We will be able to accomplish the same task in a single pointing with SING. Akshaya et al. [7] have found an unexplained component of the diffuse UV radiation field at the Galactic poles. Unfortunately, this cannot be diagnosed with only imaging data from GALEX and will form one of our prime targets, where we have the ability to make a significant scientific contribution with a modest instrument. Although our primary science is in the spectroscopy of diffuse sources, we will also obtain spectra of any point source in the field with a resolution of about 3000. If we have control of the pointing, we may be able to observe transients (supernovae and other explosive events) in the UV, providing crucial diagnostics [8]. Observations of absorption lines in the spectra of stars combined with emission-line observations of (for example) molecular hydrogen in the line of sight will yield precise information about the physical conditions of the gas in the line of sight. In general, any investigation into a previously unexplored region will yield new science. It is fortunate for us that the UV offers us just such an opportunity where even a modest instrument can make important discoveries.

3. Instrument Summary

Our most important science drivers were a spectral resolution of about 0.1 nm (spectral resolution about $R = 1500$) with a spatial resolution better than 13 arcsec over the wavelength range from 125 to 300 nm. A list of spectral lines of our science interest is presented in the Table 1.

We have achieved the requirements through a Cassegrain design (see its description below). Our detector is a copy of a MCP-based photon counting detector (Fig. 1) developed by Ambily et al. [9]. This detector is now being used in multiple payloads and may be customized depending on the wavelength region of interest. The instrument will be calibrated at our calibration facility in IIA (Indian Institute of Astrophysics). This facility was used for the integration, characterization and calibration of the UVIT instrument [10]. In order to mitigate the impact of contamination, the telescope assembly and alignment will be performed in class 1000 clean rooms,

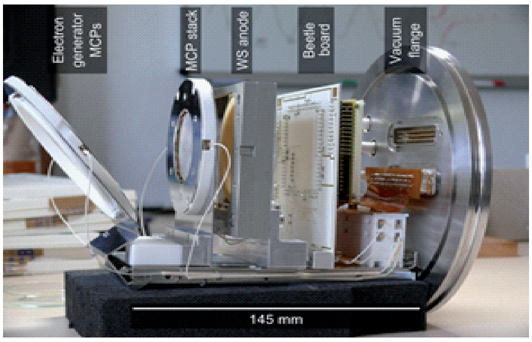


Figure 1: Laboratory model of SING detector.

with laminar flow tables providing class 100 locally. Procedures will be adapted from the UVIT calibration using equipment from the UVIT and Aditya programs will be used. The complete instrument will be stored in a sealed container purged with ultra-clean nitrogen after final assembly.

4. Relevance of the CSS

Our primary scientific requirement is to map nebulae and other extended objects at moderate spatial and spectral resolution in the ultraviolet (130–230 nm). The requirement for ultraviolet data is that much of the dynamics and energetics of a region are shown through their effect on emission and absorption lines of atoms and molecules. These are all electronic transitions and are largely in the ultraviolet, including lines from different phases of the interstellar medium. Observations in the ultraviolet must be done above the Earth's atmosphere (the ozone layer). The technology is proven with a heritage of space based instruments and presents no challenges but the science is unique with the potential to make new discoveries. We are fortunate that the ultraviolet is still amenable to exploration with relatively small instruments which may be built with limited funds and in a short time period. The Space Station provides a relatively stable platform for observations over a long time period. Surprisingly, there has not been a UV astronomical experiment on a space station so far, except for the Glazar UV imaging telescope on-board the Mir Space Station. However, its sensitivity was lower than was expected and only images of O, B or early A type stars (brightest stars in the UV) were obtained on the Glazar. Despite the limited sensitivity, these observations produced several new results that improved our understanding of O, B stars and their formation [11]. There have been a number of missions, including the spectrographs on the Hubble Space Telescope, which have observed specific locations and obtained diagnostics on the local energetics and dynamics. However, nebulae are complex and filamentary and physical conditions vary across the objects. With a long duration observation plan on the CSS, we will have the freedom to obtain a spectroscopic survey of the sky — a unique resource which we will make freely available for further study.

5. Preliminary optical layout of the SING

The total volume of the SING spectrograph is $589 \times 350 \times 402$ mm^3. There are two limiting constraints on this: i) the detector, which requires 2U of the total 6U structure; and ii) the optics whose size is determined by the plate scale. The total weight of the payload is 12.5 kg with an aluminum structure and a power usage of 9 W. We have not included heaters in this estimation. The optical elements are off axis parabolic mirror, concave grating both made up of Zerodur coated with Al + MgF_2, CaF_2 corrector lenses and an MCP based detector. The optical layout of the instrument is shown in Fig. 2.

Incoming light rays will be collected and focused by the off axis parabolic mirror. The focused beam will then pass through a long narrow slit of dimension $1.15\,\mathrm{mm} \times 17.52\,\mu\mathrm{m}$. Beyond the slit, the rays are diffracted by a concave grating. Diffracted rays from the grating passes through a corrector lenses and finally focused onto the detector plane, generating an image of the source's spectrum (Fig. 3). The detector front consists of a photo cathode and Micro Channel Plate. UV photons striking the photocathode generate secondary electrons, cascading through the pores of MCP, resulting in a cloud of electrons emerging from the MCP and impinging on the phosphor screen. This electron cloud generates a flash of visible photons, which are channeled through a fiber taper onto the CMOS detector. We have analysed and optimized the design with Zemax and the spot diagram (simulated PSF) for the system at central wavelength is shown in Fig. 4.

We have optimized the optical design with minimum optical components for maximum optical efficiency. The effective area of the instrument is determined by the reflectivity of the zerodur mirror and grating, the grating efficiency, the CaF2 lens transmission, and the detector quantum efficiency. Based on vendor data, we have estimated a minimum effective area of 6 cm^2 across the bandpass. We employ an MCP based photon counting

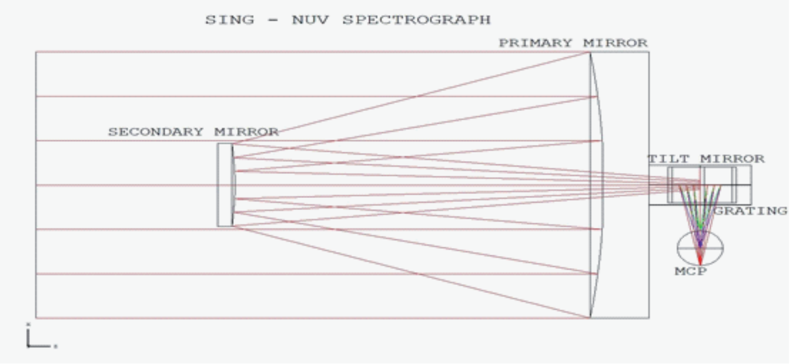


Figure 2: SING Optical Layout.

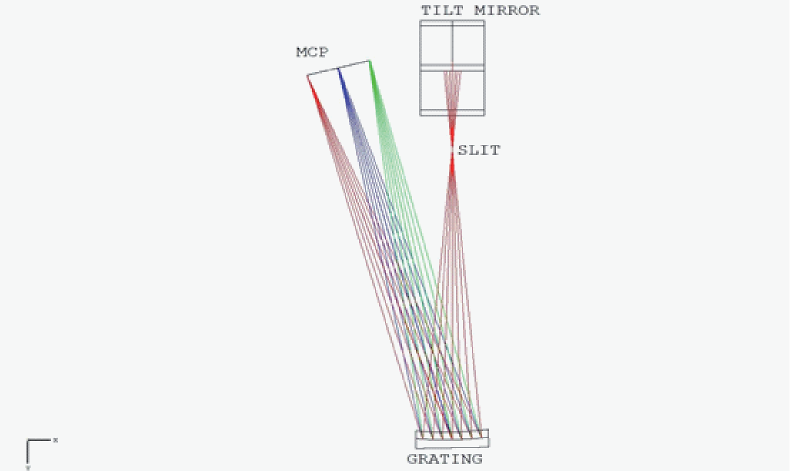


Figure 3: SING Spectrograph.

detector with zero read noise and very low dark current so that the noise is determined by photon statistics of Poisson distribution. The instrument will be mounted on the antiSun direction of the space station to scan the sky.

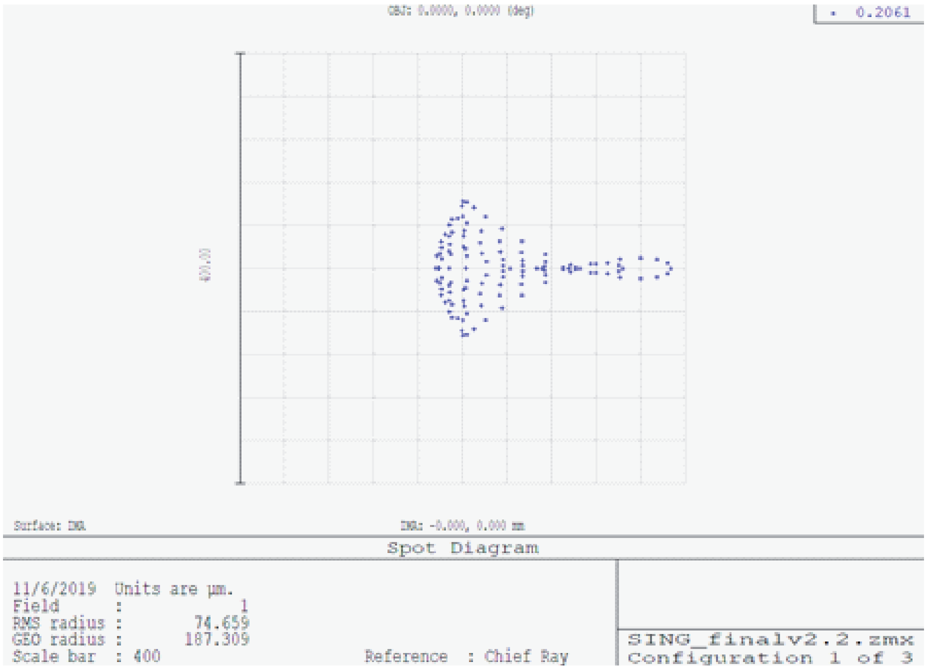
We have shown a simulation of lines from the Helix Nebula and that of a 13th magnitude O-type star obtained from CALSPEC calibration database (Fig. 5. The detector counts are estimated for a 0.1 nm bandpass and we have calculated a limiting sensitivity of 10^{-14} ergs cm^{-2} A^{-1} s^{-1} for an SNR of 3 in a 1000 s exposure, which may be achieved with multiple visits, if necessary. We have also compared this photon levels with a diffuse continuum source of a 100 photons cm^{-2} A^{-1} s^{-1}, where we assume the main contribution to the background coming from the zodiacal. We have the necessary sensitivity and resolution to map the emission from these extended objects in a single 20-minute exposure.

6. Conclusions

SING is a compact spectrograph, specifically designed to study emission lines from extended regions. This unique design would enable us to measure and analyse large areas of the sky within the stipulated mission duration.

The Space Station provides a relatively stable platform for observations over a long time period. SING would be the first UV spectrograph ever on-board a space station. With a long duration observation plan on the CSS, we will have the freedom to obtain a spectroscopic survey of the sky — a unique resource which we will make freely available for further study. All components will be Mil-standard but will be sourced from qualified vendors. We have adopted this philosophy in our other space payloads and have found it to serve well for payloads of this class.

We have baselined a three year delivery of the flight model from the start of the proposal. This is an ambitious timeline but achievable given our groups experience with UVIT and VELC (on Aditya) as well as IIA small payload development program and INASAN WSO-UV program. We have identified vendors capable of delivering space quality hardware within set timelines.



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11/6/2019  Units are µm.
Field      :          1
RMS radius :     74.659
GEO radius :    187.309
Scale bar  : 400                        Reference  : Chief Ray
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SING_finalv2.2.zmx
Configuration 1 of 3
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Figure 4: Spot diagram for 206.1nm.

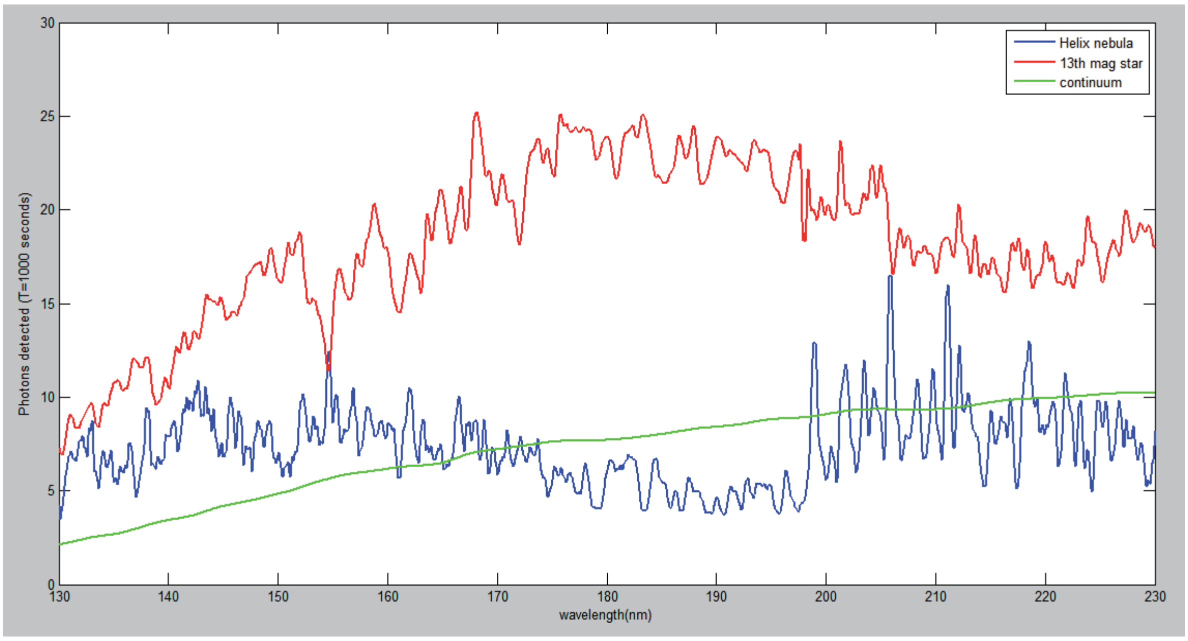

Figure 5: Simulation of 1000 second observation of the Helix Nebula and a 13th mag O star by SING. A diffuse continuum of 100 photons $\mathrm{cm}^{-2}\,\mathrm{A}^{-1}\,\mathrm{s}^{-1}$ is also plotted

The longest lead item in the whole payload is the detector which will be fabricated at IIA. We have had experience in procuring, fabricating and testing similar detectors. Procurement for the laboratory optics will be done immediately on commencement of the project.

The science team has been chosen for their expertise in the development of space instruments and in their expertise in the specific science topics chosen: from supernovae to galaxy clusters. The lead institute (IIA) is experienced in developing UV missions and the PI has over 30 years experience in ultraviolet astronomy. The Russian team is involved in the WSO-UV mission with its two UV spectrographs [12] and also has had decades of experience in UV astronomy.

The ground calibration of the instrument will be carried out at IIA. This facility was used for the integration, characterization and calibration of the UVIT instrument.

The most important outcomes are the new knowledge of nebulae in the sky. We will obtain physical conditions of the interstellar medium over a number of different phases, from the cold phase to the hot phase through observations of their line emission and absorption. We will develop manpower through the use of students for the instrument design and the following analysis of the science. These students will continue on to contribute to the space industry in both academic and industrial settings.

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