PROJECT

6

PLANETARY NEBULAE

Objective: The purpose of this exercise is also twofold. The first one is to become familiar with the analysis of narrow band images and the second is to examine the spatial distribution of the extinction that an object suffers. The absorption is mainly influenced by the Earth's atmosphere as well as by processes related to the nebula itself. Interstellar absorption is also present and can be significant depending on the actual distance of the object and its location in the galaxy.

Observations: The students will make use of a robotic telescope to acquire images in the hydrogen emission lines (H_α and H_β) of a planetary nebula (the same procedure can be followed in the case of an emission line nebulae, e.g. a supernova remnant. Clearly, the physics between the two classes of objects differ but the reduction process will still remain the same.). Images of standard stars in order for calibration purposes are also needed.

- Flat field frames, 4 in each filter (H_α, H_β, and continuum filter)
- Bias frames, a total of 10 spanning over the night
- Object frames, 1 at each filter (minimum). e.g. for NGC 6720
- Standard star frames, 10, at least, at 3 different airmasses

Theory topics: Planetary nebula, narrow filters, interstellar and atmospheric extinction

Analysis: The first task is to determine the atmospheric extinction and correct the planetary nebula images for this effect. Subsequently, they will perform the necessary operations in order to map the effects of the intrinsic and interstellar absorption in a two dimensional image.

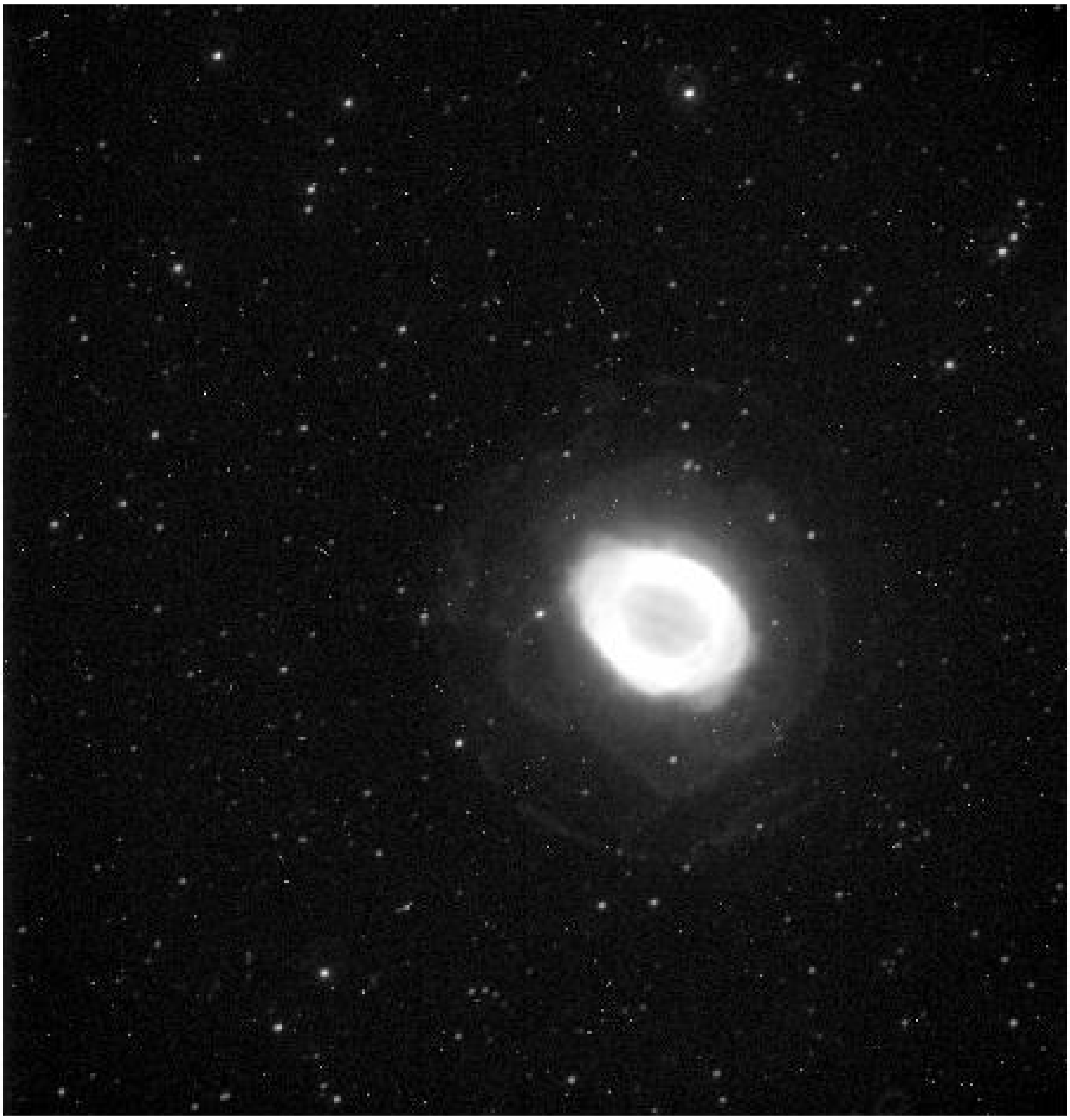

Fig. 1 A raw image of the planetary nebula NGC 6720 in the H_β filter.

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1. INTRODUCTION

Interstellar extinction, due to scattering and absorption processes, leads to a significant reduction of the light as it travels through space. The whole process is wavelength dependent and several studies exist that attempt to determine the actual shape of the optical extinction curve (e.g. Whitford, A.J., 63, 201, 1958). In general, shorter wavelengths are more absorbed than longer wavelengths.

Since planetary nebulae are emission line nebulae their intensity at any wavelength can be written as

$$I_{\lambda} = I_{o\lambda} e^{-cf(\lambda)}$$

Here I_{λ} is the intensity at a wavelength λ before it enters the Earth's atmosphere. $I_{o\lambda}$ is the intensity at the same wavelength at the location of the object and *c* is the actual amount of extinction. However, $I_{o\lambda}$ cannot be known a priori and a combination of lines is required. Usually, the Balmer lines Hα and Hβ , at 6563 Å and 4861 Å, are used as

$$\frac{I_{H\alpha}}{I_{H\beta}} = \frac{I_{oH\alpha}}{I_{oH\beta}} e^{-c(f(H\alpha)-f(H\beta))} \quad (1)$$

The term $f(H_{\alpha})$-$f(H_{\beta})$ is known from the adopted interstellar extinction curve, $I_{H\alpha}$ and $I_{H\beta}$ are the two-dimensional images to be obtained from optical observations and c is the actual extinction map that we would like to construct. $I_{oH\alpha}$ and $I_{oH\beta}$ are the images that would be recorded if there were no interstellar extinction. It is clear that it is not possible to obtain observationally such images. Fortunately, theoretical physics show that for the conditions usually found in planetary nebulae the ratio

$$\frac{f_{oH\alpha}}{f_{oH\beta}}$$

is close to 3.0. Under the above assumptions we can solve for c as

$$c = \frac{-1}{f(H\alpha) - f(H\beta)} \ln\left(\frac{I_{H\alpha}/I_{H\beta}}{3.0}\right) \quad (2)$$

and the result will also be an image and not a single number. The extinction map can now be studied in detail. If there is no intrinsic absorption then a flat image would be expected and an average value would represent the extinction towards the specific PN. However, any large scale variations in the map will imply intrinsic absorption and further studies are required to resolve its origin and structure. You should keep in mind that we are recording information in 2D space, while the emission processes originate in 3D space.

There is a very important and basic step before proceeding with scientific studies of emission line nebulae. For example, it is well known that the ratio of specific emission lines may be used to determine the temperature of the emitting gas, e.g. $(I_{6548}+I_{6583})/I_{5755}$ (lines emitted from single ionized nitrogen [NII]). Similar ratios of other lines allow us to study the ionization structure or the distribution of elemental abundances in a nebula. In all cases, the ratios must be corrected for the effects of interstellar extinction. Otherwise wrong results will be obtained. Emission in the continuum is possible and observations using appropriate continuum filters are necessary. However, you don't have to perform this step for the purposes of this exercise.

2. PROCESSING

Arrange your observation schedule so that you observe a number of standard stars, listed in Table I, in a range of airmasses. Try to include the airmass of your target in the corresponding range of your standard stars. Select the exposure times in a way that the photon counting errors are small without overexposing the CCD camera. You must also take care that the target observations are performed sequentially in order to avoid aligning the images. It is clear that in order to obtain proper results the nebular images must be projected to a common origin on the sky. This process is described elsewhere.

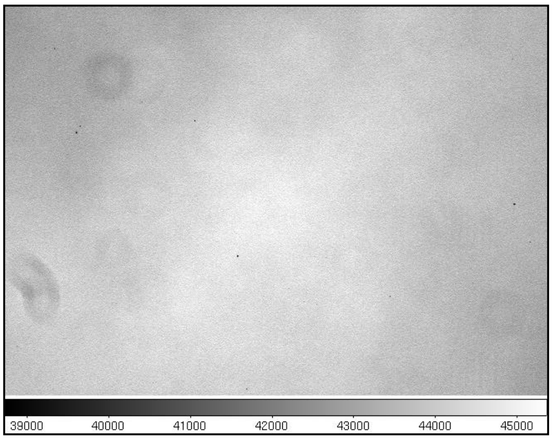

Fig. 2. A raw image of a flat field frame

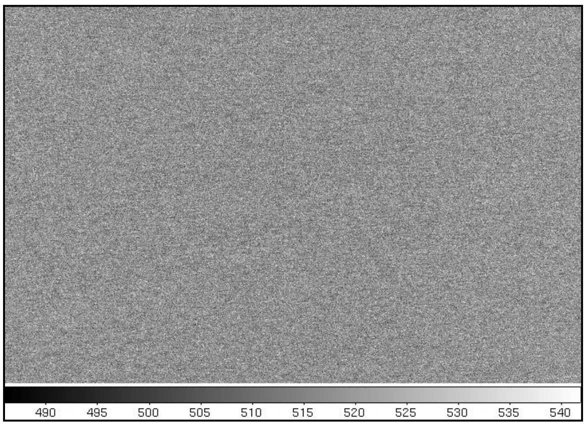

Fig. 3. A bias frame shows a uniform distribution

Narrow band or interference filter images are, initially, processed in a similar manner like broadband images. However, this is true up to the stage where instrumental magnitudes are obtained. The processing after this step differs significantly. Let's see in more detail the analysis of the spectrophotometric standard stars. The interference filters are characterised by full width half maxima of ~10-20 Å and it is reasonable to expect that the atmospheric absorption, the quantum efficiency of the CCD and the response of the telescope optics are basically constant over the band pass. Then, the light recorded by the CCD, after passing through the Earth’s atmosphere and the telescope optical system, can be expressed as

$$N(adu) = A_o 10^{-0.4k\chi} \frac{t\exp}{hc} \int N_{star}(\lambda) T_F(\lambda) \lambda d\lambda \qquad (3)$$

where

- N_{star} is the total source counts,
- A_o is the zero point of the magnitude scale,
- k is the extinction due to our atmosphere,
- χ is the airmass of the star during the observation,
- t_{exp} is the exposure time in sec,
- h is Planck's constant in CGS units,
- c is the speed of light ic CGS units,
- $T_F(\lambda)$ is the transmission of the filter as a function of wavelength,
- $N_{star}(\lambda)$ is the known energy distribution of the standard star in erg /sec/ cm^2/Å.

Reducing this relation to magnitudes and rearranging terms, we obtain

$$-2.5\log(\frac{N(adu)}{t_{\exp}}) + 2.5\log(\frac{1}{hc} \int N_{star}(\lambda) T_F(\lambda) \lambda d\lambda) = -2.5\log(A_o) + k\chi \qquad (4)$$

and the free parameters that we seek are A_o and k.

The measured parameters are the instrumental magnitude, the airmass during the observation and the exposure time in seconds. The value of the integral depends on the specific standard star and filter. These are supplied for a number of bright stars and filters in Table I and for conditions typical to Skinakas Observatory.

It is evident that the corrected magnitude varies linearly with the airmass and a linear fit of the left hand side of eq. (4) vs. airmass would determine the slope k and the y-intercept -2.5\ log(A_o). You can write your own program to perform the fit or use any spreadsheet program with fitting capabilities. Once k and A_o are determined, you can proceed to calibrate the object (PN) data. In the case of an unknown star, we can only calculate its integrated flux by reverting eq. (3) and calculating the integral part, since A_o and k are now known. This is what would be measured if the telescope was placed at the top of the Earth's atmosphere.

The object data are also processed in the usual way (bias, flat field, etc.) but in addition, the sky background must be subtracted. In order to perform this action, select several areas in your image which are free from nebular emission and measure the sky background. Write down and examine these intensities along with the standard deviation given by the software. Use an average value if the values agree within the errors, otherwise the construction of a two dimensional sky background image should be considered. Once the sky level has been subtracted, the calibration procedure can be applied.

However, equation (3) cannot be used because we are now dealing with an extended object and its flux should be calculated per unit sky projected area. The slightly modified form of equation (3) reads

$$N_{ij}(adu) = A_o 10^{-0.4k\chi} \frac{t_{\exp}}{hc} N_{ij}(\lambda_o) T_F(\lambda_o) \delta^2 \qquad (5)$$

It was assumed that any emission line behaves like a delta, δ(x), function at λ_o and the integral is simply evaluated at this wavelength measured in Angstrom. The indices ij refer to pixel coordinates in the image where the observed intensity is N_{ij} in adu. The transmittance of the Hα line in the corresponding filter is 0.23, while that of the Hβ line is 0.53. A_o and k are already determined through the calibration process. The airmass χ is a weighted average because during long exposures the actual airmass varies substantially. You can use the following formula for the effective airmass:

$$\chi = \frac{\chi_{start} + 4\chi_{middle} + \chi_{end}}{6} \qquad (6)$$

The exposure time is typically several hundreds seconds since planetary nebulae are faint objects, while δ is the pixel size of the CCD in arcseconds. Consult the Skinakas operator for the actual value of δ used during your observation. If the pixels of the camera are not squared, then δ^2 should be replaced by the product δ_x δ_Y. The transmittance of the filter at the specified wavelength λ_o of the emission line is $T_F(\lambda_o)$.

Equation (5) can be solved for the unknown flux $N_{ij}(\lambda_o)$ which will be a two dimensional image in units of erg/sec/cm^2/arcsec^2. It describes the flux from the planetary nebula at the wavelength of λ_o that we would observe if the telescope was located at the top of the Earth's atmosphere. The image is now calibrated and can be used for further scientific analysis. If there are more than one image available in the same filter, the calibration procedure must be applied to each one of them. In order to obtain the final image, you can average the individual frames available at each nebular line (e.g H_{α}, H_{β}) after properly aligning them. The final images are the ones that will be entered in equation (2) to calculate the extinction map.

Table I - Standard Star Properties

Standard star	HR9087	HR718	HR4468	HR5501	HR7596	HR7950
V magnitude	5.12	4.28	4.70	5.68	5.62	3.78
Right Ascension	00 01 49	02 28 10	11 36 41	14 45 30	19 54 45	20 47 41
Declination	-3 01 39	08 27 36	-9 48 08	00 43 03	00 16 25	-9 29 45
Integral $I_s(H_{\alpha})$	6.5E-7	1.3E-6	8.9E-7	3.6E-7	4.2E-7	2.1E-6
Integral $I_s(H_{\beta})$	4.5E-6	8.6E-6	6.1E-6	2.3E-6	2.4E-6	1.4E-5