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Exposure time calculator for IFOSC and sky background estimation

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Abstract. This paper describes a spectroscopy exposure time calculator for the faint object spectrograph, the "IUCAA Faint Object Spectrograph" (IFOSC). It is intended to provide reasonable estimates of exposure times for observations. The background sky brightness is modeled for different phases and angular distance from the Moon. The code automatically calculates the Lunar Ephemerides from the date and time of observations and uses it for sky brightness computations. We adopt a new technique of scaling the Rayleigh and the Mie scattering functions, according to the corresponding extinction terms. This estimation of the sky brightness with moonlight fits reasonably well with the observed sky brightness measured at the IUCAA telescope site.

A simple component model is used for the optical elements. Each component is described by simple wavelength dependent extinction tables. At present, a blackbody/power-law spectrum is chosen as the input spectrum. Model or actual spectrum can also be used. The input blackbody spectrum is computed using the stellar "*Spectral type*" and scaled by the apparent V magnitude of the star. The programme is easily configurable for different sites and instruments. The code is written in *ANSI C* and thus portable to any system. A graphically interactive interface using *HTML-cgi* script has also been developed.

Keywords : telescopes – instrumentation: spectrographs – methods: observational – techniques: spectroscopic – scattering – atmospheric effects

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1. Introduction

A 2-m optical telescope is being set up by IUCAA on a hill near Godegaon (about 80 km north of Pune) (Longitude $\phi_L = 73\overset{\circ}{.}667$, Latitude $\phi_l = 19\overset{\circ}{.}083$ and at a height of 1005 m above sea level). The first light back-end instrument for this telescope will be a faint object spectrometer and camera, which is called the "IUCAA Faint Object Spectrometer & Camera" (IFOSC). The main features of IFOSC are its wide wavelength coverage, large field of view and possibility of low and medium resolution spectroscopy with a large selection of grisms and filters etc. The instrument is a modified version of EFOSC made at ESO, and it was designed and fabricated at the Copenhagen University Observatory; the collimation-camera combination was first designed at ESO and subsequently the design was modified at IUCAA to suit the constraints of manufacturing. The front end of IFOSC consists of a calibration unit containing the spectral lamps, integrating sphere etc. and has been designed and developed at IUCAA. For more details on the IUCAA 2 m Telescope and IFOSC, see Gupta et al. (2002). A report on characterization of the site for IUCAA telescope was done by Das et al. (1999). The key details about the site, the telescope and the IFOSC can also be found in Gupta et al. (2002).

Exposure time calculator (ETC) is an extremely necessary tool for the preparation of any observations. It provides us *a priori* with a reasonably good idea about the observations we wish to undertake and assists us greatly in proposal preparation. Most instruments on major telescopes have such a calculator to aid its observers to plan their observations. Here we describe a spectroscopic ETC for IFOSC on IUCAA 2m telescope. It is intended to provide reasonable estimates of the signal-to-noise (S/N) ratio for an observation with a given exposure time. The transmittance and the flux is computed for different components on the path of the star light.

ETC requires a background sky brightness estimator. The major source of variation of the background sky is due to the Moon. The background sky brightness is modeled for different phases and angular distance from the Moon. Lunar and Solar ephemerides are computed and from it the Lunar position (α_m, δ_m), the phase angle φ of the Moon and the Moon-Object angular distance ρ are calculated. The sky-brightness is modeled, using a two component scattering model consisting of Mie and Rayleigh scattering functions. We adopt a new technique of scaling the Rayleigh and Mie scattering functions in accordance to their corresponding extinction.

A simple component model is used for the optical elements. Each component is described by simple wavelength dependent extinction tables. The input spectrum can be a library spectrum from a database or simply a blackbody spectrum. A blackbody spectrum is computed using the "*Spectral type* to T_{eff}" conversion and scaled by the apparent V magnitude of the star. For a library spectrum, the data file pertaining to the specific star or star type, could be read. The programme is easily configurable for different sites and instruments. The code is written in *ANSI C* and thus portable to any system. The user interphase is in *HTML-cgi* script which enables the observer to use the ETC over the internet.

2. Transmittivity calculation

The total transmittance $T_0(\lambda)$ can be separated out as the product of different transmittances due to different components in the path of the incoming light.

$$\begin{aligned} T_0(\lambda) &= T_{atm}(\lambda, X) \cdot T_{tel}(\lambda) \cdot T_{slit}(s, \Lambda(\lambda)) \cdot T_{col}(\lambda) \\ &\qquad \cdot T_f(\lambda) \cdot T_{grism}(\lambda) \cdot T_{cam}(\lambda) \cdot QE_{CCD}(\lambda). \end{aligned} \tag{1}$$

$T_{atm}(\lambda, X)$	:	Transmittivity of the atmosphere which depends on wavelength λ, and the airmass X.
$T_{tel}(\lambda)$	:	Transmittivity of the telescope inclusive of the total telescope obscuration.
$T_{slit}(s_w, \Lambda(\lambda))$	:	Transmittivity through the spectrograph slit. This quantity depends on the slit-width s_w and the seeing $\Lambda(\lambda)$ (point-spread) of the object.
$T_{col}(\lambda)$	:	Transmittivity through the collimator. This quantity depends on the number of lenses and the transmittance of the different coated glasses used for the lenses.
$T_f(\lambda)$	:	Transmittivity through the order separating filter. In the present setup, an order separating filter will only be used with the grism $IFOSC13$.
$T_{grism}(\lambda)$	:	Transmittivity through the grisms. For Echelle, this quantity will be a product of the transmittance of both the grisms used.
$T_{cam}(\lambda)$	:	Transmittivity through the camera and the field lens. This quantity depends on the number of lenses and the transmittance of the different coated glasses used for the lenses.
$QE_{CCD}(\lambda)$	:	Response or the Quantum efficiency of the CCD.

2.1 Atmospheric transmittivity $T_{atm}(\lambda, X)$

The atmospheric transmittance is given by

$$T_{atm}(\lambda, X) = e^{-[k(\lambda) \cdot X]}, \tag{2}$$

where $k(\lambda)$ is the extinction at zenith and X is the airmass. The extinction $k(\lambda)$ essentially depends on Rayleigh type extinction, aerosol dust (Mie) type extinction, and ozone absorption. Rayleigh type extinction dominates the blue while the red region of the spectrum is dominated by aerosols. Bessell (1990) using the formula of Hayes and Lantham (1975) provided an atmospheric extinction term for ozone, Rayleigh and aerosol. These terms were derived from empirical fits to the optical and UV ozone and to Rayleigh scattering from molecules and aerosol components. It would have been ideal to derive such a formula by fitting the observed atmospheric extinction at the IUCAA telescope site. Unfortunately, at present, we only have two data points of the observed atmospheric extinction at the telescope site measured in B (4400Å) and V (5500Å) bands by Das et al. (1999).

$$k_B(4400\text{Å}) = 0.46 \text{ airmass}^{-1} \qquad k_V(5500\text{Å}) = 0.28 \text{ airmass}^{-1}. \tag{3}$$

In the absence of more data points, we will directly make use of the extinction formulation given in Bessell (1990) which we reproduce here.

$$\begin{aligned}
\text{Ozone}: \quad k_O(\lambda) &= 1.11 \cdot 0.25 \cdot 2.5 \cdot \{1210 \cdot exp[-0.0131(\lambda - 2600) \\
&\quad +5.5 \times 10^{-2} \cdot exp[-1.88 \times 10^{-6}(\lambda - 5900)^2]\} && (4)\\
\text{Rayleigh}: \quad k_R(\lambda) &= 9.5 \times 10^{-3} \cdot exp(-h_o/8) \cdot (10^4/\lambda)^4 \cdot \{0.23465 + \\
&\quad 107.6/[146 - (10^4/\lambda)^2] + 0.93161/[41 - (10^4/\lambda)^2]\}^2 && (5)\\
\text{Aerosol}: \quad k_A(\lambda) &= 0.087 \cdot exp(-h_o/1.5) \cdot (10^4/\lambda)^{0.8} && (6)
\end{aligned}$$

In the above equations wavelength λ is in Å to keep it consistent with this paper and h_o is the observing height in km. We set the parameter $h_o = 0$ to derive the fit to the observed atmospheric extinction measured by Das et al. (1999). Fig. 1 shows this fit. This fit $k(\lambda) = k_O(\lambda) + k_R(\lambda) + k_A(\lambda)$ will be used for wavelength dependent extinction calculation of the ETC until a better formulation of the extinction is possible with more wavelength dependent data on extinction is available from the telescope site.

In Fig. 1 we have also over-plotted a simple two component extinction model $k_s(\lambda) = A + B/\lambda^4$, where extinction due to aerosols is assumed to be wavelength independent (large size grains are assumed), while extinction due to Rayleigh is proportional to λ^{-4}. From Fig. 1 we see that $k_s(\lambda)$ fit deviates from $k(\lambda)$ fit for wavelengths $\lambda > 6500$Å. The parameters A and B determined by this fit will be later used for weighting the scattering function in modeling the scattered moon light in Section 3.

2.1.1 *Airmass Calculation*

For calculation of the airmass X, the effect of the spherical earth must be used. The most common polynomial approximation was made by Bemporad in 1904 and is given in Hardie (1962) as:

$$X = \sec Z - 0.0018167(\sec Z - 1) - 0.002875(\sec Z - 1)^2 - 0.0008083(\sec Z - 1)^3. \tag{7}$$

We will make use of this equation (Eq. 7) for calculation of the airmass for computing atmospheric transmittance (Eq. 2). The zenith distance Z or $\sec Z$ should be determined

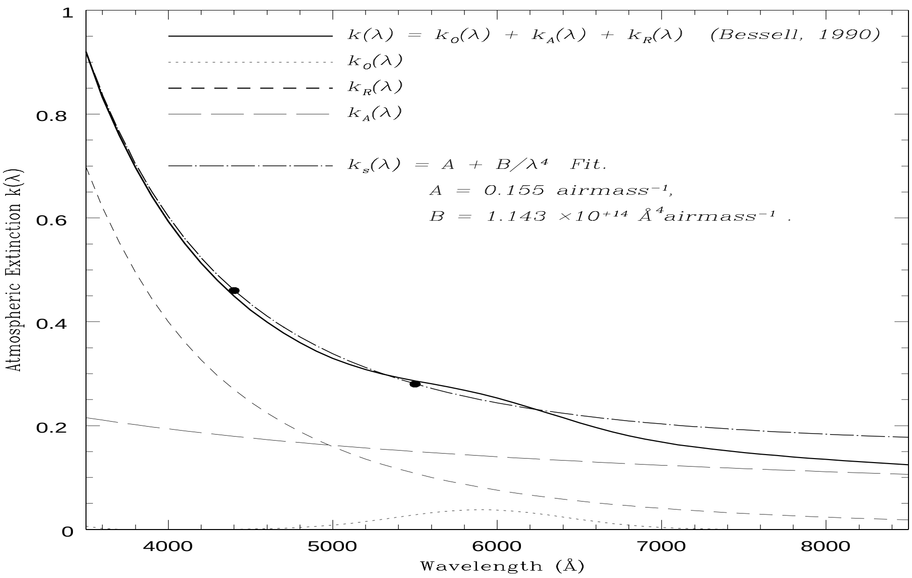

Figure 1. Atmospheric extinction. Fit using the extinction formulation given in Bessell (1990) and a simple two component model.

from the inputs provided by the observer. That is, $\sec Z$ should be found as a function of Right Ascension α_0, Declination δ_0, time of observation U_T (in UT) and date D_t of observation.

$$\sec Z = (\sin\phi_l \sin\delta_0 + \cos\phi_l \cos\delta_0 \cos H)^{-1} \tag{8}$$

where ϕ_l is the observers latitude and H is the hour angle in degrees of the star. The latitude for IUCAA telescope is $\phi_l = +19°5'$ N. The hour angle H can be calculated by

$$H = LST - \alpha_0, \tag{9}$$

where LST is the Local Sidereal Time. The Local Sidereal Time is computed by

$$LST = GST + \left(\frac{366.2422}{365.2422}\right) U_T + \frac{\phi_L}{15}, \tag{10}$$

where GST is the Greenwich Sidereal Time and is defined as the Greenwich Hour Angle of the vernal equinox. The quantity GST can be calculated from Julian date using the parameters D_t and U_T. The derivation for GST can be found in any standard book on Astronomical Methods such as that of Bradt (2004). The term ϕ_L is the observers Longitude ($\phi_L = 73°40'$ E for IUCAA telescope location).

2.2 Transmittivity of the telescope $T_{tel}(\lambda)$

Transmittivity of the telescope $T_{tel}(\lambda)$ will essentially depend on both primary and secondary mirrors and the telescope obscuration. For the IUCAA telescope the total obscuration is about 18.5% (*TTL Manual for IUCAA Telescope*). For our calculations we take $T_{tel}(\lambda) = 0.7$ (*i.e* 70%) as a constant with wavelength. This value is inclusive of the telescope obscuration correction. A better estimation of $T_{tel}(\lambda)$ could be made after the commissioning of the telescope.

2.3 Transmittivity through the spectrograph slit $T_{slit}(s, \Lambda(\lambda))$

We assume the star to have a Gaussian point spread function due to seeing $\Lambda(\lambda)$ ($\Lambda(\lambda) \equiv FWHM = 2\sqrt{2\ln(2)} \cdot \sigma(\lambda)$). Distribution of star light as a Gaussian function can be written as

$$\begin{aligned} I(r)dr &= \frac{I_0}{2\pi\sigma^2} \cdot e^{-r^2/2\sigma^2} \cdot rd\theta dr \\ &= \frac{I_0}{2\pi\sigma^2} \cdot e^{-(x^2+y^2)/2\sigma^2} \cdot dxdy, \end{aligned} \tag{11}$$

where I_0 is the total flux received from the star and $r = \sqrt{x^2 + y^2}$ is the distance from the centroid.

Assuming that the slit with slit-width s_w blocks some of the star light in the x-direction, the light passing through the slit will be:

$$\begin{aligned} I'_0 &= \frac{I_0}{2\pi\sigma^2} \cdot \int_{-\infty}^{+\infty} e^{-y^2/2\sigma^2} dy \cdot \int_{-s_w/2}^{+s_w/2} e^{-x^2/2\sigma^2} dx. \\ &= \frac{I_0}{2\pi\sigma^2} \cdot \sqrt{2\pi}\sigma \cdot \sqrt{2\pi}\sigma Erf\left(\frac{s_w}{2\sqrt{2}\sigma}\right) = I_0 \cdot Erf\left(\frac{s_w}{2\sqrt{2}\sigma}\right). \end{aligned} \tag{12}$$

The transmittance through the spectrograph slit will be

$$T_{slit}(s_w, \Lambda(\lambda)) = \frac{I'_0}{I_0} = Erf\left(\frac{\sqrt{\ln(2)} s_w}{\Lambda(\lambda)}\right). \tag{13}$$

It is found that image size $\Lambda(\lambda) \propto \lambda^{-0.2}$ (Glass, 1999). If the seeing through the V filter ($\lambda_V = 5500$Å) is Λ_V then,

$$\Lambda(\lambda) = \left(\frac{\lambda_V}{\lambda}\right)^{0.2} \cdot \Lambda_V. \tag{14}$$

We will assume Λ_V as the expected seeing in V filter at the observatory ($\Lambda_V = 1.5$ arcsec at IUCAA telescope site).

2.4 Transmittivity through the collimator $T_{col}(\lambda)$ and the camera $T_{cam}(\lambda)$

The transmittance through the collimator and the camera ($T_{col}(\lambda)$ and $T_{cam}(\lambda)$) depends on the number of lenses and the transmittance of the different coated glasses used for the lenses.

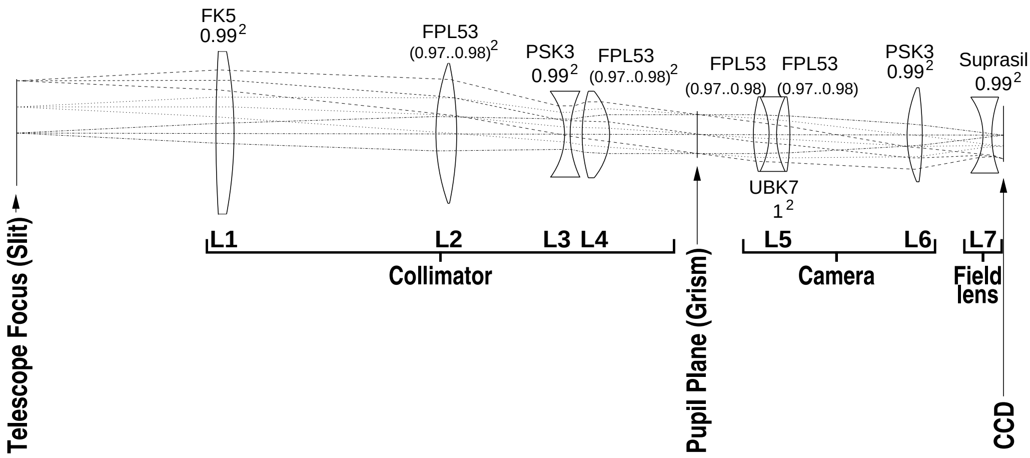

Figure 2. The optical layout of IFOSC. The caption along with each of the lenses in the collimator, the camera and the field lens, indicates the coated glass material used and its average transmittance. The optical ray drawing shows the telescope focus, the pupil plane and the instrument focus on the CCD plane. Collimator focus $f_{col} = 315.7$ mm and camera + field lens focus $f_{cam} = 141.8$ mm.

The optical layout of IFOSC is shown in Fig. 2. Reflectance (*i.e.* 1.0−Transmittance) from each surface of the coated glasses which constitute the lenses ($FK5$, $FPL53$, $PSK3$, and $Suprasil$) have been provided by the optics supplier. The transmittance of each lens is multiplied for computing $T_{col}(\lambda)$ and $T_{cam}(\lambda)$. Though physically the field lens (L7) is part of the CCD camera, its transmittance is included into $T_{cam}(\lambda)$. For purpose of transmittance calculation the lenslet L5 made of $FPL53$, $UBK7$ and $FPL53$ is considered as a single lens of $FPL53$.

2.5 Transmittivity through the grisms $T_{grism}(\lambda)$ and transmittivity through the order-separating filter $T_f(\lambda)$

The transmittance through the grisms $T_{grism}(\lambda)$ are taken from the wavelength dependent transmittance graphs available at the Danish 1.54-m telescope DFOSC website[1].

[1] *http://www.ls.eso.org/lasilla/Telescopes/2p2T/D1p5M/misc/dfosc_grisms.html*

Table 1 in Gupta et al., (2002) provides the wavelength range of each grism. The grism "*IFOSC 9*" which will be used in Echelle mode with the grisms "*IFOSC10*", "*IFOSC11*" and "*IFOSC12*" as cross-disperser, has a average efficiency close to 40% (38% to 46%) for all orders from order 8 to order 20. We will therefore assume, *IFOSC 9* to have a constant transmittance of 40% for all wavelength from 3500Å to 8500Å. This 40% transmittance of grism *IFOSC 9* will be weighted by the transmittance of grism used as the cross-disperser (*IFOSC 10*, *IFOSC 11* and *IFOSC 12*). The grism *IFOSC 13* will be used only in the 3^{rd} order with an order separating filter. The transmittance of grism *IFOSC 13* is therefore weighted by the transmittance of the order separating filter $T_f(\lambda)$. The transmittance $T_{grism}(\lambda)$ along with the grism names, and average grism resolutions $\delta\lambda_0$, has been tabulated and will be used by the code.

3. Estimation of the background sky radiation $B(\lambda, t)$

The sky background can contribute significant Poisson noise and must be taken into account during noise calculations. The source for the background sky radiation $B(\lambda, t)$ can be separated into;

1. The faint unresolved stars and galaxies on the line of sight of the observation contributes to this background.
2. Star/Sun light is scattered by interstellar, interplanetary, and atmospheric dust (The zodiacal background light is part of it). This scattered light along with the air glow, that enters the telescope beam, also contributes to this background.
3. Moon light essentially scatters from our atmospheric dust and molecules.
4. Light pollution from city/villages around the observatory.

The sky background may vary due to clouds which can either decrease the background by blocking the sky or increase the background by scattering more moon light and artificial light from ground sources.

The sky background brightness estimated at the IUCAA telescope site by Das et al. (1999) are 21.8, 20.9 and 19.5 mag/arcsec^2 in B, V and R bands. We will assume this background to be the zenith background B_{zen} on a moonless night.

From the available $B_{zen}(\lambda)$ in B, V and R filters, extrapolation is necessary to obtain $B_{zen}(\lambda)$ beyond R filter up to $\lambda = 8500$ Å and before B filter up to $\lambda = 3500$ Å. This extrapolation is made assuming blackbody functions. For wavelengths $\lambda > 7000$ Å to 8500 Å, a blackbody curve is fitted to $B_{zen}(V)$ and $B_{zen}(R)$. Similarly, another blackbody curve is fitted to $B_{zen}(B)$ and $B_{zen}(V)$, for shorter wavelengths (for $\lambda < 4400$Å to $\lambda = 3500$ Å) (see Fig. 3). For flux calibration, $m = 0.0$ mag offset was taken from Allen (2000) for an *A0 V* star.

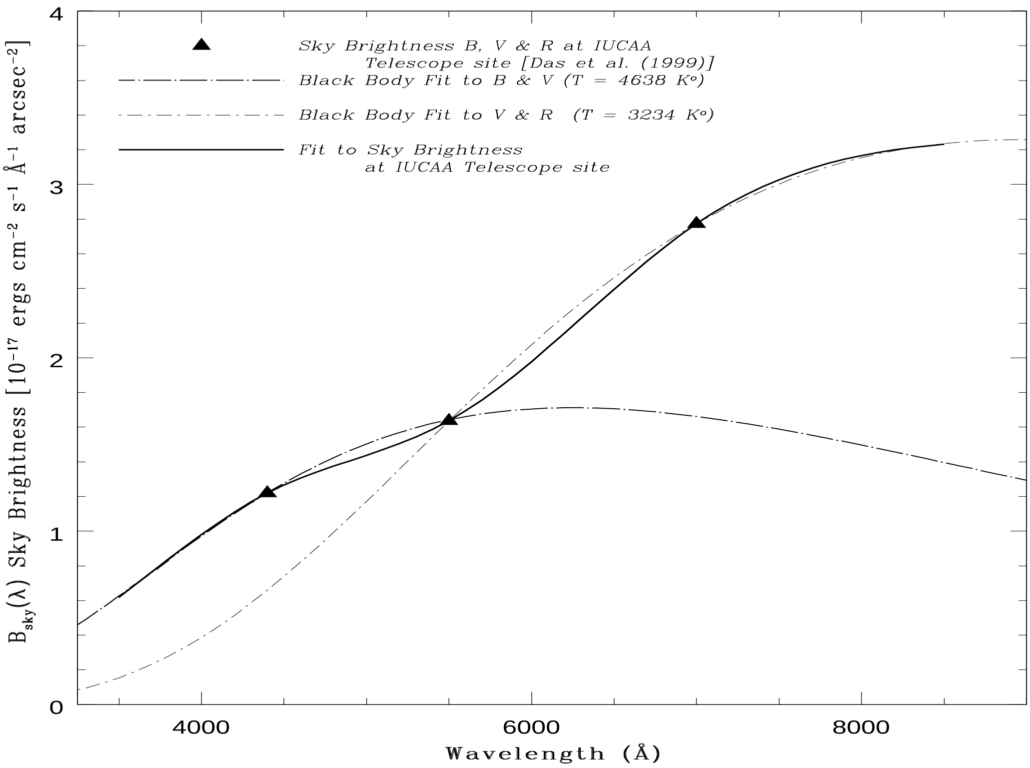

Figure 3. Zenith background $B_{zen}(\lambda)$ on a moonless night at the IUCAA telescope site.

The optical sky background depends on a number of parameters including the object-Moon angular separation ρ, lunar phase φ, ecliptic latitude, zenith angle, and phase of the solar cycle (e.g. Krisciunas (1997); Krisciunas and Schaefer (1991); Benn and Ellison (1998)). The sky variation due to the phase of the solar cycle is very small compared to other uncertainties and therefore it will not be considered. $B_{zen}(\lambda)$ will have a contribution from the Zodiacal light and the light pollution from city etc. Apart from these contributions, any other variations in the sky brightness without the Moon light ($B_0(Z,\lambda)$), due to Zodiacal light and light pollution from specific sources from the nearby cities/villages are not considered.

To estimate the night sky background, we make use of a model constructed by Krisciunas and Schaefer (1991). We make use of (Eq. 2), (Eq. 3), (Eq. 15), (Eq. 20) and (Eq. 21) from their paper. The sky background $B(Z, Z_m, \varphi, \rho, \lambda)$ is modeled by two parts,

$$B(Z, Z_m, \varphi, \rho, \lambda) \quad = \quad B_0(Z, \lambda) + B_{moon}(Z, Z_m, \varphi, \rho, \lambda), \tag{15}$$

where $B_{moon}(Z, Z_m, \varphi, \rho, \lambda)$ is the additional sky background due to the moonlight. The parameters Z is the zenith angle of the object of study, Z_m is the zenith angle of the

Moon, φ the phase of the Moon and ρ is the angular distance of the Moon from the object. The sky background $B_0(Z,\lambda)$ relevant for man-made light scattered by the atmosphere is of the form

$$B_0(Z,\lambda) = B_{zen}(\lambda)\cdot\left(\frac{1-e^{-k(\lambda)\cdot X}}{1-e^{-k(\lambda)}}\right). \tag{16}$$

Krisciunas and Schaefer (1991) in their model of the brightness of moonlight have used

$$B_0(Z,\lambda) = B_{zen}(\lambda)\cdot X_s\cdot 10^{-0.4k(\lambda)(X_s-1)}, \tag{17}$$
$$X_s = (1-0.96\sin^2 Z)^{-0.5}, \tag{18}$$

which is a simplification from Garstang (1989) describing essentially the sky brightness due to the night glow. Though Eq. 17 is more appropriate for night glow, we have used it instead of Eq. 16, to parametrize the moonless sky background observed at the IUCAA telescope site and find that an acceptable fit is obtained (see Fig. 4). The extinction coefficient $k(\lambda) = k_O(\lambda) + k_R(\lambda) + k_A(\lambda)$ has already been defined in Eq. 4-4. The coefficient X_s is the optical path-length along a line of sight in units of airmass. Note that the formula for X_s in Eq. 18 is appropriate for night glow and is different from the airmass X definition in Eq. 7. According to Krisciunas and Schaefer (1991), X_s defined in Eq. 18 gives a better fit of observed lunar brightness vs model brightness, for a very large range of $B_{moon}(Z, Z_m, \varphi, \rho)$. Thus, we might call X_s in Eq. 18 as the "scattering airmass" and X in Eq. 7 as the "extinction airmass".

For sky background due to moonlight $B_{moon}(Z, Z_m, \varphi, \rho)$, we will use the derivation by Krisciunas and Schaefer (1991),

$$B_{moon}(Z, Z_m) = f(\rho)I^* 10^{-0.4k(\lambda)X_s(Z_m)}[1-10^{-0.4k(\lambda)X_s(Z)}]. \tag{19}$$

Here $f(\rho)$ is the scattering function which needs to be evaluated (The Moon-Object angular distance ρ, is equivalent to the scattering angle) and I^* is the illumination of the moon.

Similar to Krisciunas and Schaefer (1991), we also take the scattering function $f(\rho)$ to be a two component term, composed of a Rayleigh scattering function $f_R(\rho)$ and a Mie scattering function $f_M(\rho)$. The Rayleigh scattering function $f_R(\rho)$ takes care for scattering from atmospheric gases, while Mie scattering function $f_M(\rho)$ is for atmospheric aerosols. The Rayleigh scattering function $f_R(\rho)$ can be represented by

$$f_R(\rho) = C_R[1.06 + \cos^2(\rho)] \tag{20}$$

(Rozenberg, 1966). C_R is the proportionality constant which we determine by integrating and normalizing $f_R(\rho)d\omega$ over the whole solid angle.

$$\int f_R(\rho)d\omega = 2\pi C_R\int_0^{\pi}[1.06+\cos^2(\rho)]\sin(\rho)d\rho = 1. \tag{21}$$

Solving the integral in Eq. 21 and unit conversion from Sr to arcsec^{-2} we get

$$C_R = 1.34 \times 10^{-12} \text{arcsec}^{-2}. \tag{22}$$

Determining $f_M(\rho)$ theoretically is extremely complicated. Since there are many free parameters, the theory is generally derived for idealized cases which have no utility for the real atmosphere. Thus the only alternative is that of empirical measurement. In our determination of $f_M(\rho)$ we will make use of the functional form for $f_M(\rho)$ given by Krisciunas and Schaefer (1991)

$$f_M(\rho) = C_M 10^{-\rho/n}. \tag{23}$$

Here $n = 40$ if ρ is in degrees. For ρ in radians $n = 2\pi/9$. The value C_M is the proportionality constant which we determine by integrating and normalizing $f_M(\rho)d\omega$ over the whole solid angle.

$$\int f_M(\rho)d\omega = 2\pi C_M \int_0^\pi 10^{-9\rho/2\pi} \sin(\rho)d\rho = 1. \tag{24}$$

Solving the integral in Eq. 24 and unit conversion from Sr to arcsec^{-2} we get

$$C_M = 4.44 \times 10^{-11} \text{arcsec}^{-2}. \tag{25}$$

For $\rho < 10°$, the data in King (1971) show that Eq. 23 is not valid. Krisciunas and Schaefer (1991) has shown that for $\rho < 10°$, $f_M(\rho)$ is of the form,

$$f_M(\rho) = C'_M \rho^{-2}. \tag{26}$$

We determine C'_M by matching $f_M(\rho)$ at the boundary (*i.e.* $\rho = 10°$). Thus, we get

$$C'_M = 10^{1.75} C_M = 2.50 \times 10^{-9} \text{arcsec}^{-2}. \tag{27}$$

For determining sky flux close to the Moon ($\rho < 10°$) we use Eq. 26. However, it has to be noted that variation of the sky flux in this region is extremely large and not uniform.

Since the scattering functions $f_R(\rho)$ and $f_M(\rho)$ have been individually normalized, the total scattering function $f(\rho)$ will have to be a weighted sum of $f_R(\rho)$ and $f_M(\rho)$ so that $f(\rho)$ is also normalized. In Sec. 2.1 we determined the parameters A and B from a simple two component extinction model $k_s(\lambda)$. These two parameters provide the proportion between $f_R(\rho)$ and $f_M(\rho)$, since scattering is directly related to the extinction. We thus use these parameters A and B to weight $f_R(\rho)$ and $f_M(\rho)$. The total scattering function $f(\rho)$ will therefore be

$$\begin{aligned} f(\rho,\lambda) &= \frac{1}{k_s(\lambda)}\left(A \cdot f_M(\rho) + \frac{B}{\lambda^4} \cdot f_R(\rho)\right) \\ &= \frac{1}{k_s(\lambda)}\left(A \cdot C_M 10^{-\rho/40} + \frac{B \cdot C_R}{\lambda^4}[1.06 + \cos^2(\rho)]\right) \quad \text{for} \quad \rho \geq 10°. \quad (28) \\ &= \frac{1}{k_s(\lambda)}\left(A \cdot 10^{1.75} C_M \rho^{-2} + \frac{B \cdot C_R}{\lambda^4}[1.06 + \cos^2(\rho)]\right) \quad \text{for} \quad \rho < 10°. \quad (29) \end{aligned}$$

The scattering angle ρ is measured in degrees in Eq. 28 and Eq. 29.

The illuminance of the Moon I^* depends on the phase φ of the Moon and on $m_0(\lambda)$ the apparent mean opposition ($\varphi = 0$) magnitude of the Moon.

$$I^* = I_0(\lambda) 10^{-0.4(m_0(\lambda)+0.026|\varphi|+4\times10^{-9}\varphi^4)}, \quad (30)$$

$$= \Phi(\varphi) \cdot I_0(\lambda) 10^{-0.4(m_0(\lambda))}, \quad (31)$$

$$\Phi(\varphi) = 10^{-0.4(0.026|\varphi|+4\times10^{-9}\varphi^4)}. \quad (32)$$

Eq. 30 has been adapted from Krisciunas and Schaefer (1991). In Eq. 31 we have separated the φ dependence as a phase law parameter $\Phi(\varphi)$ (Allen, 1976). In Eq. 32, φ is in degrees.

The relation $\Phi(\varphi)$ in Eq. 32, ignores the "opposition effect". For $|\varphi| \leq 7^\circ$ the brightness of the Moon deviates from this relation (see Whitaker, 1969). This factor only comes into play within the full Moon night. On a full Moon night ($|\varphi| \leq 7^\circ$), the moonlight is brighter than the extrapolation would predict, assuming, of course, that it is not undergoing a penumbral or umbral eclipse. We tackle the lunar opposition effect by assuming $\Phi(\varphi) = 1$ for $|\varphi| \leq 7^\circ$. This implies that the moonlight is maximum for phase angles $|\varphi| \leq 7^\circ$, on a full Moon night. The small changes in Moon's brightness on a full Moon night due to changes in $|\varphi|$ within 7° can be ignored for sky brightness calculations.

Lane and Irvine (1973) note that observations before full Moon appear systematically brighter ($\lesssim 0.1$ mag in V) than points after at equivalent phase angle. They also find that the value of the phase integral, normally assumed to be independent of wavelength, to increase with the wavelength. This difference is very small and is caused by the scattering properties of different regions on the Moon. In the later edition (4^{th} edition) of Allen (2000) the Moon's polynomial function phase law (Eq. 32), has been replaced by the Lunar integral phase function taken from Hapke (1962). The value of the Lunar integral phase function from Hapke (1962) is different before and after full Moon. We see Hapke's Lunar integral phase function has a very small deviation from $\Phi(\varphi)$ ($RMS = 1.17 \times 10^{-2}$ before Full-Moon and $RMS = 1.82 \times 10^{-2}$ after Full-Moon). For our purpose, this deviation is negligible. Thus for the *ETC* we will still make use of polynomial relation of $\Phi(\varphi)$ given in Eq. 32. The advantage for using Eq. 32 is that it is in a functional form and can be calculated on the fly during estimation of the sky background in our code. We will also not consider the wavelength dependence of $\Phi(\varphi)$ as quoted by Lane and Irvine (1973), since its effects are also very small.

The Lunar Mean Flux at opposition ($\varphi = 0$ Full Moon) for U, B, V, R and I were computed from V magnitude and colour given in Table 12.14 of Allen (2000) and Table 17 from Harris (1961). For flux calibration, $m = 0$ mag offsets for each filter were taken from Allen (2000) for an $A0\ V$ star. A cubical spline interpolation was made for determining the flux at intermediate wavelengths.

Using Eq. 15 to Eq. 32 we can now calculate the sky background $B(Z, Z_m, \varphi, \rho)$ on the fly. The term Z has already been determined in (*Sec.* 2.1.1). The terms Z_m, φ and

ρ of the Moon can be derived from Date D_t and Time U_T of the observation and the coordinates (RA, DEC) of the object. The Lunar and Solar Ephemerides calculations have been included in the code.

4. Verification of the estimated model background sky radiation $B(\lambda, t)$

The estimated model background sky radiation $B(\lambda, t)$ was observationally verified. Observations were made at the telescope site with a wide angle CCD camera, which consists of a $f/1.8$, 6.5mm wide angle lens mounted on a ST6 CCD camera. Standard B, V, and R filters were used in front of the lens. Flats for these observations were obtained by placing an opal glass diffuser on top of the filter and a diffused source (the evening sky), was observed. The wide angle lens was kept a little out of focus to increase the stellar psf to $\sim$3 pixels so that stellar photometry could be performed for calibrating the sky and determining the atmospheric extinction for that day. The observations were made on January 1, 2004. The atmospheric extinction computed from observations were $k_B = 0.38 \pm 0.06$ airmass^{-1}, $k_V = 0.27 \pm 0.04$ airmass^{-1} and $k_R = 0.15 \pm 0.03$ airmass^{-1}. The parameters $A = 0.121 \pm 0.032$ airmass^{-1} and $B = (1.03 \pm 0.27) \times 10^{14}$ Å^{4}airmass^{-1} (Sec. 2.1) were determined by least-square fitting of the extinction *vs.* $1/\lambda^4$ plot to determine $k(\lambda)$. These values of the parameters A and B with their associated errors where used for determining the model sky brightness. The sky background without the Moon $B_0(Z, \lambda)$ was observed after the Moon had set. Fig. 4 shows the variation of moonless sky brightness with the zenith distance. The observed moonless sky brightness fits reasonably well with the estimated $B_0(Z, \lambda)$ from Eq. 17 within the uncertainty. We then compared the observed moonlit sky background with the estimated $B(Z, Z_m, \phi, \rho)$ (Eq. 15). Since $B(Z, Z_m, \phi, \rho)$ is dependent on many parameters (Z, Z_m, ϕ, ρ), we therefore chose to compare the difference between the observed moonlit sky background and the estimated $B(Z, Z_m, \phi, \rho)$ as a function of angular distance ρ from the Moon. Fig. 5 shows the difference between observed and estimated model background sky radiation in B, V and R filters. The circled points are for the sky brightness observations made on high cirrus clouds which gives us an estimate of the change in the sky brightness due to these clouds. From the plots in Figs 4 and 5 we obtain a strong confidence in estimating efficiently the sky brightness at the IUCAA telescope sight. The estimation should also work for other sites when $k(\lambda)$ and $B_{zen}(\lambda)$ are provided for the site.

5. The flux $F(\lambda)$ from the objects

The Spectral Type *SpType* of the star is used for determining T_{eff} of the star. A look-up table of *SpType* and T_{eff} has been made from Allen (2000), Colina (1995) and Lang (1982).

A blackbody spectrum is constructed using T_{eff}. This blackbody spectrum is scale

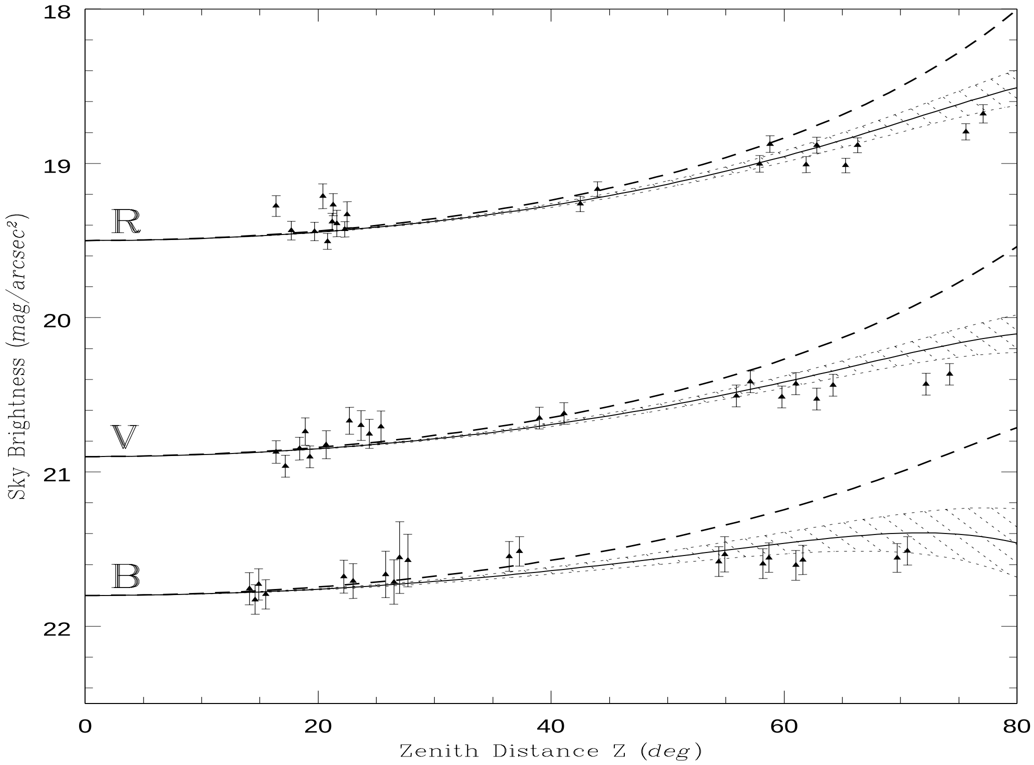

Figure 4. Variation of observed moonless sky brightness with the zenith distance in B, V and R filters at IUCAA Telescope site. Over-plotted is Eq. 17 with $B_{zen}(\lambda)$ estimated by Das et al. (1999). The hashed region around the curve is the uncertainty in estimation of $B_0(Z, \lambda)$ from Eq. 17 due to the errors in $k(\lambda)$. Over-plotted is also Eq. 16 (dashed line) which deviates from observations at about $z = 50°$.

to observed V magnitude m_V for determining $F(\lambda)$.

$$F(\lambda) = F_{V0} \cdot 10^{0.4 m_V} \cdot \frac{B(T_{eff}, \lambda)}{B(T_{eff}, \lambda_V)} \tag{33}$$

where $\lambda_V = 5500\text{Å}$ and $B(T_{eff}, \lambda)$ is the blackbody spectrum. For flux calibration, $F_{V0} = 3.75 \times 10^{-9} erg\ cm^{-2} s^{-1} \text{Å}^{-1}$ is the $m_V = 0\ mag$ offset for an $A0\ V$ star Allen (2000). Instead of a blackbody spectrum, Kurucz model stellar atmosphere or the spectral database by Silva and Cornell (1992), can easily be used. The look-up table of *SpType* and T_{eff} already contains an additional information for using Kurucz model stellar flux or the spectral database by Silva and Cornell (1998). Instead of determining T_{eff} of the star, relevant data file containing model flux or database spectra is selected. The

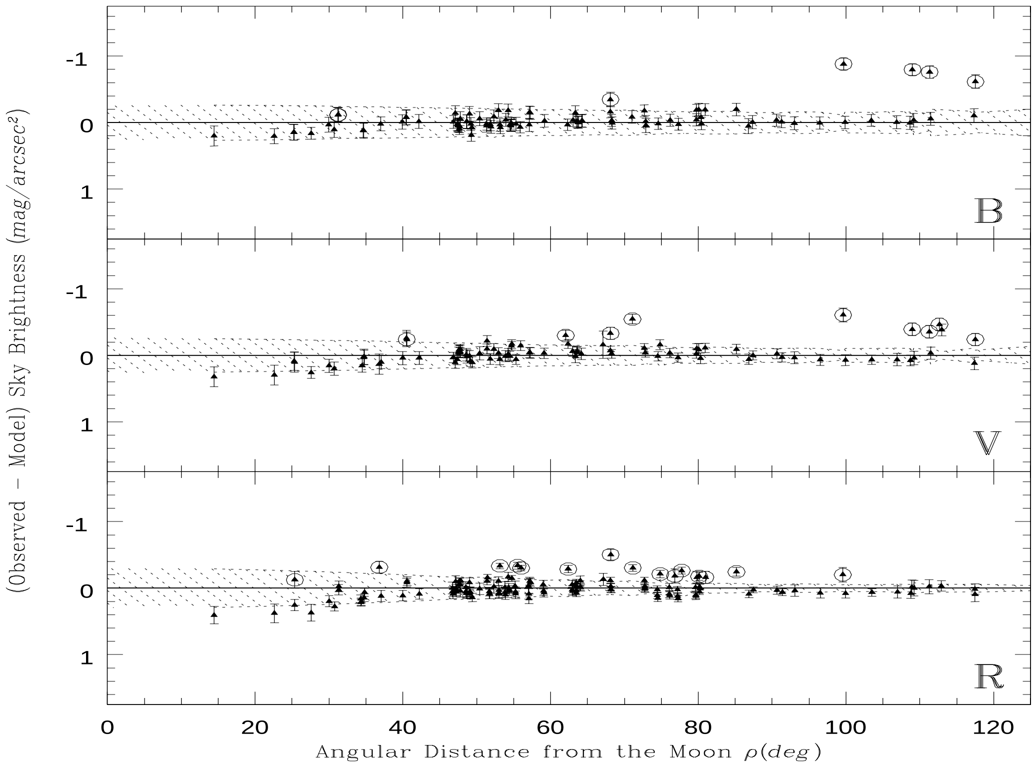

Figure 5. Difference between observed and estimated model background sky radiation in B, V and R filters. The circled points are for the sky brightness observations made on high cirrus clouds. The hashed region again here is the uncertainty in the estimation of $B(Z, Z_m, \phi, \rho)$ due to the errors in $k(\lambda)$.

Kurucz model stellar fluxes are created using Kurucz (1992) LTE model atmosphere [2]. The spectral database by Silva and Cornell, (1992) consists of spectra of 72 different stellar types, covering 3510-8930Å at a resolution of 11Å. In addition, instead of a stellar spectrum a power-law spectrum

$$F(\lambda) = F_{V0} \cdot 10^{0.4 m_V} \cdot \left(\frac{\nu}{\nu_V}\right)^{-\alpha} = F_{V0} \cdot 10^{0.4 m_V} \cdot \left(\frac{\lambda_V}{\lambda}\right)^{-\alpha} \tag{34}$$

could also be used with spectral index $\alpha \lesssim 1$, for non-stellar objects. Such a power-law spectrum has relatively far more energy at high frequencies compared with a blackbody spectrum (Padmanabhan, 2002). As stellar spectrum, this power-law spectrum is scaled by m_V in the same manner as in Eq. 33.

[2]This Kurucz stellar flux data can be obtained from:
http://www.stsci.edu/science/starburst/Kurucz.html

6. Signal to noise calculations

Here below, is the procedure we adopt to calculate the expected S/N for an observation using the IFOSC on IUCAA telescope.

The signal registered by the instrument, which includes the signal from the sky-background, can be represented by

$$S(\text{in e}^-) = T_0(\lambda) \cdot A_T \cdot (F(\lambda) + A_{bg}B(\lambda)) \left(\frac{\delta\lambda(s, \delta\lambda_0)}{E_{ph}(\lambda)}\right) \cdot t + n_{pix}N_D t. \tag{35}$$

where,

$T_0(\lambda)$	:	The total Transmittivity.
A_T	:	The total light collecting Area. For IUCAA 2m telescope $A_T = 3.1416 \times 10^4$ cm^2
$F(\lambda)$	:	The Flux from the object (erg cm$^{-2}s^{-1}$Å^{-1}),
$B(\lambda)$	:	The Background Sky (erg cm$^{-2}s^{-1}$Å^{-1}arcsec^{-2}),
A_{bg}	:	The Area of the sky over which the flux is summed (in $arcsec^2$). $A_{bg} = s \times A_p$. The term s_w is the slit-width and A_p is the aperture size in the spatial direction (both in arcsec).
n_{pix}	:	Total Number of pixels used in measuring the flux. $n_{pix} = A_{bg} \times (3.26)^2$. The camera plate-scale is 3.26 pixels/arcsec (pixel size = 13.5μ).
$E_{ph}(\lambda)$	:	Energy per photon $E_{ph}(\lambda) = hc/\lambda = (1.986 \times 10^{-8}\text{erg Å})/\lambda$ (h is the Planck's constant and c is the speed of light).
$\delta\lambda(s_w, \delta\lambda_0)$	:	The small wavelength interval (in Å) over which the flux is summed. *i.e.* the Resolution for a slit-width s_w in arcsec. $\delta\lambda_0$ is the resolution for $s_w = s_{w_0} = 1$ arcsec. $\delta\lambda_0$. The resolution $\delta\lambda_0$ is provided for all the grism in Table 2 of the IFOSC manual [Table 1 in Gupta *et al.*, (2002)]. $\delta\lambda(s, \delta\lambda_0) = s \cdot \delta\lambda_0$.
λ	:	The Wavelength (Å).
t	:	The Exposure time (s).
N_D	:	The Dark current ($ADU\ s^{-1}$). For EEV CCD, $N_D = 0.1e^-/pixel/hour \equiv 0.06ADU/pixel/hour$ at $153K$ (Typical).

For simplicity, let us denote,

$$K_0(\lambda) = \frac{T_0(\lambda) \cdot A_T}{E_{ph}(\lambda)}. \tag{36}$$

The signal to noise (S/N) (Howell, 1992) :

$$S/N = \frac{K_0(\lambda) \cdot F(\lambda)\delta\lambda \cdot t}{\sqrt{K_0(\lambda)\left[F(\lambda) + A_{bg}B(\lambda)\right]\delta\lambda \cdot t + n_{pix}(N_D \cdot t + {N_{ro}}^2)}}, \tag{37}$$

Here N_{ro} is the readout noise $N_{ro} = 6.3\ e^-$ (For EEV CCD) and $N_{ro} = 10.0\ e^-$ (For Loral CCD). In Eq. 37 we neglect the error in the estimation of the background $B(\lambda)$ (*i.e.* $n_{pix}/n_B \ll 1$). The term n_B is the total number of pixels used for background estimation. In the signal to noise calculations, Eq. 37 shows that the signal is background-subtracted while calculating the noise the background $A_{bg}B(\lambda)$ is included with the signal $F(\lambda)$. The signal to noise denoted by Eq. 37 is for an extracted spectrum where sky has been subtracted.

The core programme in the ETC which calculates the signal to noise, is written in ANSI C. The user interface is a web based graphically interactive $HTML$, *cgi* script. Presently it can be accessed online through the IUCAA webpage from:

http://meghnad.iucaa.ernet.in/~pavan/ETC/ETC.html

7. Parameters to be provided by the observer

For running the exposure time calculation, the following parameters have to be provided by the observer.

1. Observation parameters.

1.1	t	:	Exposure time.
1.2	U_T	:	Time of observation (in UT).
1.3	D_t	:	Date of observation.

2. Object Parameters.

2.1	*SpType*	:	Spectral type of the star (*i.e.* *A*0 *V*) or Blackbody temperature (T_{eff} in K°, Eq. 33) or Power-law spectrum α. ($C\nu^{-\alpha}$, Eq. 34)
2.2	m_V	:	Observed V magnitude of the star.
2.3	α_0	:	Apparent Right Ascension of the object.
2.4	δ_0	:	Apparent Declination of the object.

3. Sky parameters.

3.1	Λ_V	:	Atmospheric seeing ($FWHM$) in V.

4. Instrument parameters.

4.1	s_w	:	Slit-width of the spectrograph (in *arcsec*).
4.2	*Grism*	:	Grism to be used.
4.3	*CrossDisp*	:	Cross dispersing grism (*IFOSC10*, *IFOSC11* and *IFOSC12*) to be used for Echelle observations. The cross dispersing grisms to be used only with *Grism* = *IFOSC9* only.
4.4	*CCD Camera*	:	The CCD camera being used - "*EEV*" or "*Loral*".

- The parameters in (1.1) goes directly into the calculation of Eq. 35 and Eq. 37.

- The parameters in (2.1 & 2.2) is used for determining $F(\lambda)$.

- The parameters in (1.2, 1.3, 2.3 and 2.4) is used for determining $B(\lambda)$.

- The parameters in (1.2, 1.3, 2.3 and 2.4) is used for determining the airmass X and $T_{atm}(\lambda, X)$.

- The parameter in (3) is used for determining the Gaussian point spread function $\Lambda(\lambda)$ of the star (Eq. 14) and the aperture size A_p for the spectral extraction. The determination $T_{slit}(s, \Lambda(\lambda))$ also uses this parameter.

- The parameters in (4) is used for determining $T_{slit}(s, \Lambda(\lambda))$, $T_{grism}(\lambda)$, $\delta\lambda(s, \delta\lambda_0)$ and $T_f(\lambda)$. $T_f(\lambda) = 1.0$ except for $Grism = IFOSC13$ when an order separating filter is used. For Echelle observation $T_{grism}(\lambda)$ will be a product $T_{grism}(\lambda)$ of the $Grism$ and $T_{grism}(\lambda)$ of the $CrossDisp$

The $HTML$ user interface where these parameters are filled by the observer, is shown in Fig. 6. To make the ETC robust, lot of checks have been incorporated. Spurious entries are checked by a warning message in red on the output page. This warning message guides the observer to parameters which are wrongly entered. For example if the date field is filled as "29 Feb 2005", a warning message stating that "2005" is not a leap year is displayed asking the user to change the date field. The code has other checks; such as, (*i*) Availability of the object above the horizon, (*ii*) Twilight brightness, and (*iii*) The proximity of the object to the moon in the sky (*i.e.* Moon's position *w.r.t.* the object), to mention a few.

The output file generated is also an $HTML$ file. It contains the user defined parameters for verification. Other parameters which are computed by the code are also displayed, such as Z, X, $X_s(Z)$, Z_m, $X_s(Z_m)$, φ and ρ. Along with phases φ of the Moon, specific information such as full Moon ($\varphi < 7°$), new Moon ($\varphi > 173°$) and even Lunar Eclipse ($\varphi \approx 0°$) are also stated. The output file then contains a table of computed sky and star magnitudes in U, B, V, R and I bands. The sky brightness is in mag/arcsec^2. $m = 0$ mag offset was taken from Allen (2000) for an $A0\ V$ star. This table is followed by another table containing information about the star flux in erg cm$^{-2}s^{-1}$Å^{-1}, the sky background flux in erg cm$^{-2}s^{-1}$Å^{-1} arcsec^{-2}, the total transmittance $T_0(\lambda)$, the Signal in e^- and the S/N at different wavelengths. The displayed signal and the S/N are for the extracted spectrum using an extraction aperture of A_p (Eq. 37).

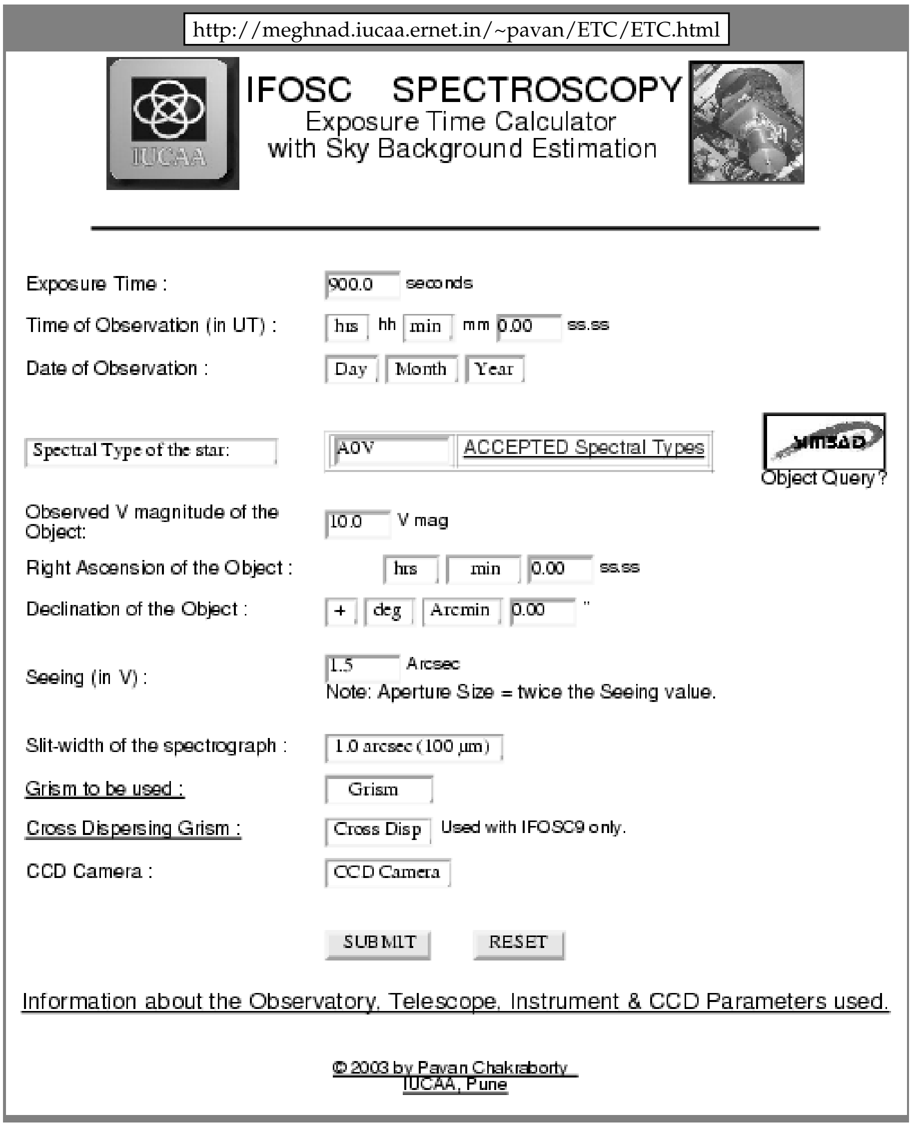

Figure 6. The HTML input interface for the ETC. This webpage is hyper-linked with other required informations which will help the observer use the ETC and plan their observations.

8. The observatories, telescope, instrument and CCD parameters

There are a set of fixed parameters normally not accessible to the observer for modification. They are essentially observatory, telescope, instrument and CCD parameters. These parameters set for IFOSC on IUCAA telescope are:

Observatory parameters.

ϕ_L	=	$+73.^\circ 667$	The observatory longitude.
ϕ_l	=	$+19.^\circ 083$	The observatory latitude.
A	=	0.155 airmass^{-1}	Two component fitting parameter for
B	=	$1.143 \times 10^{+14}$Å^4 airmass^{-1}	$k(\lambda)$, used in the modeling moonlit sky.
A_p	=	$3.0 \times \Lambda_V$ (in arcsec)	Assumed aperture size for spectral extraction.

Telescope parameters.

T_{tel}	=	0.7	Telescope efficiency ($1.0 \equiv 100\%$) .
A_T	=	$10^4\pi$ cm^2	Telescope light collecting area.
$Pscl_T$	=	10.0 arcsec/mm	Telescope plate-scale.

Instrument parameters.

$Pscl_{cam}$	=	44.0 μ m/arcsec	Camera plate-scale.

CCD parameters (EEV CCD).

$pixsize$	=	13.5 μm	Pixel size (square pixel).
$Pscl_{CCD}$	=	3.26 pixel/arcsec	Camera plate-scale in pixel.
$Gain_{CCD}$	=	1.8 e^-/ADU	CCD gain.
N_{ro}	=	6.3 e^- (3.5 ADU)	CCD read out noise.
N_D	=	0.1 e^-/pixel/hour	Dark current at 153K (typical).

These parameters are defined as a separate header file "Observatory_Inst.h" which needs to be modified if the observatory, telescope and CCD are changed. The basic requirements for modifying the code for other observatories are the observatory, telescope, instrument and CCD parameters. They have to be modified accordingly by editing the file "Observatory_Inst.h" and re-compiling the code. In case of change of observatory, the sky background brightness at zenith $B_{zen}(\lambda)$ estimated at the observatory, on a moonless night, is required. The values $B_{zen}(\lambda)$ is read from a text tabular form as an input file "Moon_Sky.dat". The wavelength dependent transmittance and response of the instrument is tabulated into two files: "Inst_Trans.dat" and Grism_T0.dat. The file "Inst_Trans.dat" contains instrumental transmittance and response for static components: Collimator $T_{col}(\lambda)$, Camera $T_{cam}(\lambda)$, CCD $QE_{CCD}(\lambda)$, while Grism_T0.dat contains the transmittance for non-static components: grisms and cross dispersers $T_{grism}(\lambda)$ and order separating filter $T_f(\lambda)$.

9. Further implementations

As a further implementation to this Exposure Time Calculator with Sky Background Estimator, a data simulator is being designed. The developed code for the Exposure Time Calculator and Sky Background Estimator are the initial modules of the simulator. The output instead of being a $HTML$ file will be a "fits" data as obtained normally from the CCD camera. The spectral dispersion functions, the trace functions and flat profiles for each grisms have been obtained from actual calibrations using $IFOSC$. These functions and profiles will be inputs to the simulator. The noise will be simulated using Poisson/gauss random number generator. This simulation tool will be extremely important for better understanding of the data reduction. This simulator will be described in detail in a separate work.

The present code was essentially written for IFOSC on IUCAA telescope and will be tested with the commissioning of IFOSC. However, this code can easily be extended to other similar focal reducer instruments.

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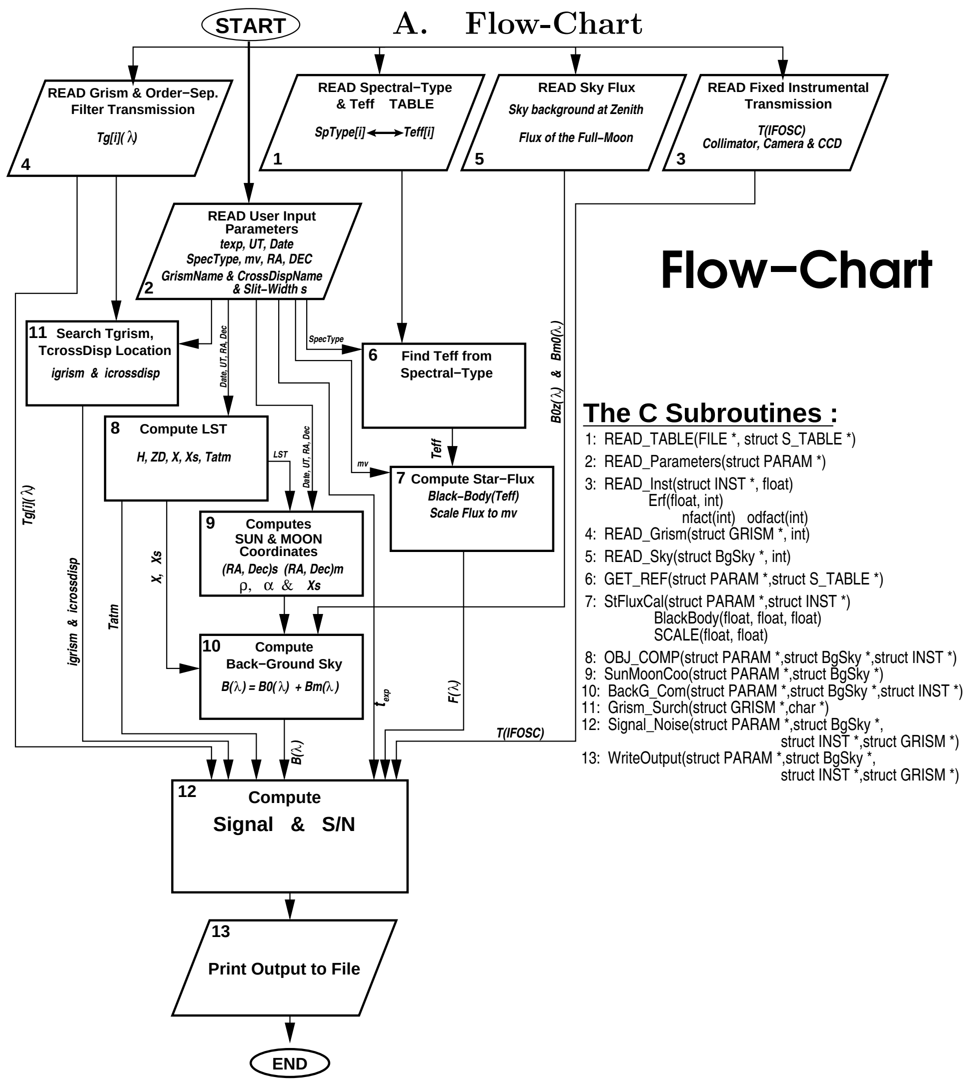
APPENDIX

The Exposure Time Calculator (ETC) code is written in C and can be used on any platform.

A. Flow-Chart



The flow-chart shown above gives a broad outline of the code. Each task box on the flow-chart is moduled into a subroutine. The C subroutines are also listed beside the flow-chart and are enumerated accordingly.