The Results of SED Simulations for a Young B–Type Star IRAS 22150+6109

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Abstract. We present the results of a spectroscopic analysis and spectral energy distribution (SED) modeling for a young B-type star IRAS 22150+6109. The optical multicolor photometric data were obtained at the Tien-Shan Astronomical Observatory near Almaty, Kazakhstan. Infrared photometry was taken from various sky surveys, such as IRAS, WISE, and AKARI. High-resolution optical spectra were obtained at the 3.6 m Canada–France–Hawaii Telescope (CFHT) and the 2.1 m telescope of the Observatorio Astronómico Nacional San Pedro Martir (OAN SPM). Fundamental parameters of the star are estimated under an assumption that it has a zero-age main-sequence luminosity and a spectral type of B3. The best fit to the SED implies that a large disk is located very far from the star (136 AU) and extended to 850 AU.

1. Introduction

IRAS 22150+6109 is an infrared source located in the direction of an active star-forming region L 1188 in Cepheus at a distance of 910 pc from the Sun (Abraham et al. 1995). We identified it with a poorly-studied $V \sim 11$ mag star found in a catalogue of early-type emission-line objects by Wackerling (1970). Results on CO emission are controversial: a negative detection by Wouterloot & Brand (1989) and a positive detection by Kerton & Brunt (2003). No emission from H_2O, OH, or CS molecules has been detected from the object (Wouterloot et al. 1993; Bronfman et al. 1996). Nevertheless, IRAS 22150+6109 exhibits a strong infrared excess that is indicative of an intermediate-mass star in transition from the pre-main-sequence to main-sequence stage of evolution. The nearly main-sequence status is supported by a weak H_α emission detected by the Hamburg survey for emission-line stars (Kohoutek & Wehmeyer 1999). It is included in a catalogue of reflection nebulae Magakian (2003). Our goal was to obtain an optical spectrum and optical multicolor photometry of the star to constrain its spectral energy distribution (SED), collect available infrared photometric data, and model the SED to derive the properties of the circumstellar dust.

Table 1. The summary of the observing dates and instruments.

Date	Telescope	Location	Resolv.power	Sp.range, Å
2004/12/24	3.6 m CFHT	Hawaii, USA	65000	4000–10500
2015/10/04	2.1 m OAN SPM	Baja California, Mexico	18000	3800–7100
2015/11/28	2.1 m OAN SPM	Baja California, Mexico	18000	3800–7100

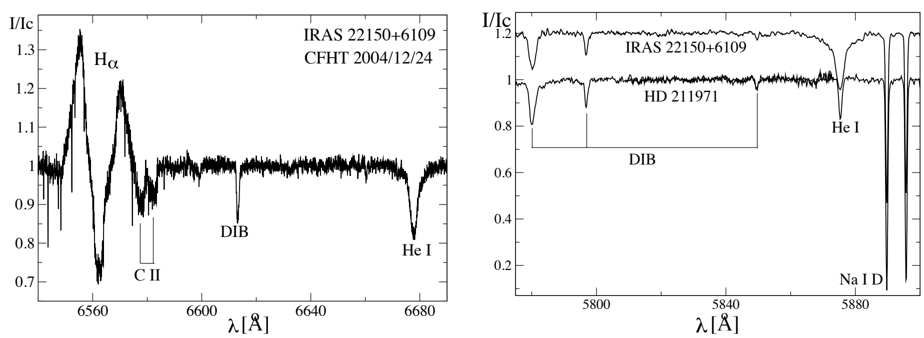

Figure 1. Parts of the IRAS 22150+6109 spectrum. *Left:* The Hα region of the CFHT spectrum. *Right:* Comparison with a spectrum of HD 211971 taken at the Three College Observatory (North Carolina, USA, resolving power $R \sim$10000). The spectra are normalized to the local continuum, the wavelength scale is heliocentric.

2. Spectroscopic Observations

We have obtained high-resolution spectroscopic observations of IRAS 22150+6109 separated by almost a decade, 2004 and 2015. The observing dates and facilities are shown in the Table 1. There are several emission features in the spectrum. The strongest one is a double-peaked Hα line (see Fig. 1). The emission peaks are separated by $\sim$ 680 km s^{-1}. This line also exhibits a narrow central emission peak at a systemic velocity of ~ -25 km s^{-1}. This peak is almost invisible in 2004 (Fig. 1) and is much stronger in 2015. No other variations were found in our spectra. Other features are very weak forbidden oxygen lines [O I] 6300 and 6364 Å and hydrogen lines of the Paschen series. The absorption-line spectrum shows moderately broad lines that are consistent with a spectral type of B3 v and a projected rotational velocity of v sin i ~200 km s^{-1}. The latter was estimated by comparison with a spectrum of η UMa (B3 v, v sin i ~150 km s^{-1}). Interstellar features in the spectrum of IRAS 22150+6109 are represented by diffuse interstellar bands (DIBs) and absorption lines of Na I (D–lines at 5889 and 5895 Å) and K I (7699 Å). The DIBs and interstellar lines strength is consistent with an optical reddening of E($B-V$) = 0.7 mag. Both the DIBs and Na I D-lines in the spectrum of IRAS 22150+6109 are very similar to those of HD 211971, an A2 Ib supergiant located in 1.5 degrees from the object and at a nearly the same distance (900 pc).

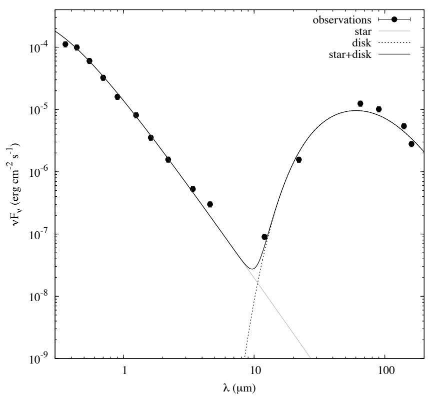

Figure 2. The observed SED of IRAS 22150+6109 with the interstellar extinction A_V = 2.0 mag removed (black dots) is shown in comparison with the best-fit face-on disk model (thick solid line). The modeled SED of the star and the disk are shown with the thin solid and dashed lines, respectively.

3. Photometric Observations

The star was observed photometrically at the Tien-Shan Astronomical Observatory (near Almaty, Kazakhstan) in the *UBVRI*–bands of the Johnson photometric system using the photometer FP3U (Bergner et al. 1988). Ten observations were obtained in 1997–1999. The photometry was published by Kuratov (2004). Infrared photometric data were collected from different catalogs. Near-IR data in the *JHK*–bands were taken from the 2MASS catalog (Cutri et al. 2003), fluxes in four bands between 3.4 and 21 μm were taken from the WISE catalog (Wright et al. 2010), and fluxes in five bands between 18 and 160 μm were taken from the AKARI catalog (Murakami et al. 2007). Fluxes measured in magnitudes were converted into energy units using zero-magnitude fluxes adopted from the listed above sources of information. Optical magnitudes were converted into fluxes using the calibration from Straizhys (1977). The optical photometry obtained during nearly 2 years shows brightness variations of 0.2 magnitude with an average of V = 10.82±0.07 mag. The average color-indices suggest the star's spectral type of B3 and an extinction of A_V = 2.0±0.1 mag. The infrared photometry was obtained at different times from 2001 to 2010, but the fluxes seem to be consistent with each other (see Fig. 2). The observed SED was dereddened using a standard interstellar extinction law from Savage & Mathis (1979).

4. Modeled Spectral Energy Distribution

We simulated SEDs of a star with an axisymmetric disk. The computation algorithm is described in Kuratov et al. (2015). However, here we used a wavelength dependent dust opacity computed with the Mie theory for spherical grains composed of astronomical silicates with a density of 2.5 $g\,cm^{-3}$, sizes a between 0.1 and 100 μm, and a grain size distribution $\propto a^{-3.5}$. We have also determined the surface density at the inner edge of the disk (Σ_{in}), based on the disk total mass (M_d):

$$\Sigma_{in} = \frac{M_d\, R_{in}^p\, (2+p)}{2\pi\, (R_{out}^{2+p} - R_{in}^{2+p})}, \qquad (1)$$

where R_{in} and R_{out} - are the disk inner and outer radii, and p is the surface density power law index (so $\Sigma_r \sim r^p$, where r is the radial distance in the disk). The computations were made for the disk of different sizes. We varied R_{in} between 2 and 1000 AU with an increment of 1 AU and R_{out} between 10 and 2000 AU with an increment of 10 AU (excluding the cases when $R_{in} = R_{out}$). A minimum value for R_{in} of 2 AU corresponds to the dust sublimation radius for the fundamental parameters of a typical B3 v star (radius and effective temperature of 5 $R_\odot$ and 20000 K, respectively) and a dust sublimation temperature is 1500 K (Dullemond et al. 2001). We varied the surface density power law p from -1.5 (as for the mass surface density of the current Solar system, Carpenter et al. 2009) to 0 (constant surface density) with an increment of 0.5. Assuming that the disk surface temperature is also a power law of the radial distance ($T_r \sim r^q$), we varied its power law index q between -0.75 and -0.35 with an increment of 0.01.

The best fit was found by minimizing the following expression:

$$\chi^2 = \sum_{i=1}^{n} \Big(\frac{F_{obs,i} - F_{mod,i}}{\sigma_{obs,i}}\Big)^2, \qquad (2)$$

where $F_{obs,i}$ and $F_{mod,i}$ are the observed and modeled fluxes (at the corresponding wavelength) respectively, $\sigma_{obs,i}$ are the observational errors that are typically $\sim$ 10% of corresponding $F_{obs,i}$ for all the data. We assume that disk emission excess only occurs at wavelengths > 1 μm, and hence we consider disk model fits only in this region.

We have found that the best fit (χ^2 = 50.82) is achieved for a system with $R_{in} = 136^{+14}_{-16}$ AU, $R_{out} = 850^{+1000}_{-250}$ AU, $p = -0.5^{+0.5}_{-1.0}$, $q = -0.65^{+0.01}_{-0.01}$, $M_d \geq 0.04 M_*$ (M_* is the mass of the star) and $i \leq 40°$. The fit parameter uncertainties are based on fits within up to 10% variation in χ^2. Fig. 2 shows the SED for the system with the best fit parameters (black line), the observations (thick filled circles) and SED of the star (thin line). The large uncertainty of the disk outer radius is due to a lack of the wavelength coverage in the far infrared spectral region. Nevertheless, our results show that the disk has been moved away from the star and is reminiscent of those of lower-mass Vega-type star debris disks.

5. Conclusions

- The optical counterpart of IRAS 22150+6109 is a spectral type B3 star surrounded by a gaseous and dusty disk. It follows from a relatively large projected rotational velocity that the stellar rotation axis (and the disk, as a consequence) is significantly tilted from the line of sight.
- The ratio of the observed projected rotational velocity to the critical velocity sets a limit on the tilt angle of the star's rotational axis of $i > 19°$.
- The interstellar features detected in the spectrum are consistent with the star's location

in the dark cloud L 1188. The presence of emission lines supports an earlier suggestion that it is a young star. This suggestion was based on the detection of the infrared excess and a reflection nebula around the star.
• IRAS 22150+6109 is a star, surrounded by a gas-rich dusty disk that has been swept away to a distance of ~70 R_{sub}.
• The SED modeling indicates that most probable disk inclination is ≤ 40°.
• The modeling predicts that the disk has a very large outer radius of 850 AU and the most probable mass of $7 \times 10^{-2} M_*$.
• The disk has a shallower density distribution that a typical accretion disk.
• Our dusty disk modeling confirms the nearly main sequence status of the star.

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