Spectroscopic and Photometric Monitoring of a Poorly Known Highly Luminous OH/IR Star: IRAS 18278+0931

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Abstract

We present the time-dependent properties of a poorly known OH/IR star, IRAS 18278+0931 (hereafter IRAS 18+09), toward the Ophiuchus constellation. We have carried out long-term optical/near-infrared photometric and spectroscopic observations to study the object. From optical R- and J-band light curves, the period of IRAS 18+09 is estimated to be \(575 \pm 30\) days and the variability amplitudes range from \(\Delta R \sim 4.0\) mag to \(\Delta J \sim 3.5\) mag. From the standard period–luminosity relations, the distance \((D)\) to the object, \(4.0 \pm 1.3\) kpc, is estimated. Applying this distance in the radiative transfer model, the spectral energy distribution is constructed from multiwavelength photometric and IRAS-LRS spectral data, which provide the luminosity, optical depth, and gas mass-loss rate of the object to be \(9600 \pm 500\ \text{L}_\odot\), \(9.1 \pm 0.6\) at 0.55 \(\mu\)m, and \(1.0 \times 10^{-6}\ \text{M}_\odot\ \text{yr}^{-1}\), respectively. The current mass of the object is inferred to be in the range 1.0–1.5 \(\text{M}_\odot\) assuming solar metallicity. Notably, the temporal variation of atomic and molecular features (e.g., TiO, Na I, Ca I, CO, \(\text{H}_2\text{O}\)) over the pulsation cycle of the OH/IR star illustrates the sensitivity of the spectral features to the dynamical atmosphere as observed in pulsating AGB stars.

Unified Astronomy Thesaurus concepts: OH/IR stars (1156); Long period variable stars (935); Spectroscopy (1558); Asymptotic giant branch stars (2100); Late-type stars (909); Observational astronomy (1145); Evolved stars (481); Period determination (1211); Near infrared astronomy (1093); Stellar astronomy (1583)

1. Introduction

OH/IR stars are a class of long-period (several hundred days) large-amplitude (1 mag bolometric) variables with a huge mass-loss rate (MLR, \(>10^{-3}\ \text{M}_\odot\ \text{yr}^{-1}\); Baud & Habing 1983) representing the thermally pulsing asymptotic giant branch (TP-AGB) phase. Due to the dust formation and copious mass loss (e.g., Höfner & Olofsson 2018) of these stars, circumstellar envelopes develop, which eventually become opaque to visible light (Habing 1996) and emit at infrared (IR) wavelengths (Bedijn 1987). OH/IR stars are oxygen-rich stars (C/O < 1, O-rich) and share many common characteristics with O-rich Mira variables, implying a close relationship between them. However, it is not well understood how they differ from each other (see Blommaert et al. 1998 for details). Moreover, O-rich stars at the TP-AGB phase evolve from a solar-metallicity star with progenitor mass either below \(2\ \text{M}_\odot\) or above \(4\ \text{M}_\odot\) (Marigo et al. 2013), and they often show OH counterparts of the name (e.g., Höfner & Olofsson 2018) of those stars, where the thermal radiation emitted by warm dust acts as a pump. The luminosity distribution of OH/IR stars peaks at around \(5000\ \text{L}_\odot\), indicating low-initial-mass \(<2\ \text{M}_\odot\) progenitors (Habing 1988; Blommaert et al. 2018). However, an appreciable number of OH/IR stars with a luminosity well above \(10,000\ \text{L}_\odot\) exist in both Galactic disk (e.g., Habing 1988) and bulge (e.g., Ojha et al. 2007), classified as a “high-luminosity group” (Jiménez-Esteban & Engels 2015), representing an evolution from relatively massive progenitors (4–6 \(\text{M}_\odot\)).

Most OH/IR stars are detected through either 1612 MHz OH surveys in the Galactic plane and Galactic center (e.g., Sevenster et al. 2001) or through various systematic surveys (for example, the Arecibo surveys; Eder et al. 1988; Lewis et al. 1990; Chengalur et al. 1993), which have been conducted for sources with IRAS (IRAS Point Source Catalog (1988)) colors resembling those of OH/IR stars (see, e.g., Olon et al. 1984). Using the same IRAS color criterion, a subclass of OH/IR stars was proposed to be preplanetary nebulae (i.e., in the post-AGB evolutionary phase), as confirmed by a Hubble Space Telescope imaging survey (Sahai et al. 2007). Such studies also resulted in the serendipitous discoveries of luminous objects that were not evolved stars (e.g., Palau et al. 2013). These previous works demonstrate the importance of studying individual IRAS sources for their characterization.

The pulsating stellar interiors of AGB stars trigger outward shock fronts, which make their atmospheres cool and very extended. As a consequence, several observational effects, e.g., modulation of the atmospheric structure, alteration of the chemical composition of the gas, effects of the velocity field on the line formation regions, and the large variation in luminosity, are seen. The shapes of the spectral energy distributions (SEDs) and the depth of the silicate features (at 9.7 and 18 \(\mu\)m) show significant variation with the pulsation phase (e.g., Suh & Kim 2002). The photometric light curves reflect the variation in brightness, surface temperature, and radius (Le Bertre 1992). Thus, a long-term monitoring program is required to study the variability properties (for, e.g., amplitudes and color variation) of this class of stars. In addition, several molecules (e.g., TiO, VO, \(\text{H}_2\text{O}\), and CO) form efficiently in their cool extended atmosphere, resulting in the typical line-rich late-type spectra. While TiO and VO bands are the dominant molecules at the optical spectra, CO and \(\text{H}_2\text{O}\) molecules shape the near-infrared (NIR) spectrum. Previous studies unveiled not only the considerable and independent variation of individual spectral features (optical TiO and VO bands: Alvarez & Plez 1998 and NIR CO, OH, and \(\text{H}_2\text{O}\) lines:...
Hinkle et al. 1982, 1984 or Lebzelter et al. 1999) over the phase but also their cycle-to-cycle variation. The line profiles of molecular lines are also affected because of the velocity field variation, while the molecular abundances in the atmosphere are influenced by the luminosity variation (Liljegren et al. 2017; Ghosh et al. 2018). Moreover, the NIR spectrum of OH/IR stars is strongly influenced by the dust, OH radical, and water content in the outer atmosphere (Bessell et al. 1996; Vanhollebeke et al. 2006). Theoretical models of O-rich stars have been successfully applied to study line profile variations and radial velocity curves found in observed spectra of long-period variables (Nowotny et al. 2010; Liljegren et al. 2017); however, no model can still interpret the exact dynamical variation of the AGB atmosphere or spectral variations at late spectral type with pulsation. Moreover, time-series spectral data are sparse in the literature, even rarer for an OH/IR star, and much needed to model the complex convective atmosphere of the AGB stars.

This paper reports spectrophotometric time-series observations of an OH/IR star, IRAS 18+09 (\(\alpha_{2000} = 18^h30^m12^s10, \delta_{2000} = +40^\circ33'42''6\)). The finding chart of the object is shown in Figure 1. The source was detected through a 1612 MHz OH maser with the Arecibo radio telescope (Olson et al. 1984). The location of the object in the IRAS two-color ([12]-[25] versus [25]-[60]) diagram signifies more evolved O-rich circumstellar shells (van der Veen & Habing 1988). The IRAS-LRS spectrum (Olson et al. 1986) of the object shows a strong silicate dust (O-rich dust) emission feature at 9.7 \(\mu\)m, indicating a group E population in the LRS spectral classification (see Kwok et al. 1997). In addition, simultaneous observations of H2O and SiO masers were recently done (Cho et al. 2017). In this paper, we study the variability properties of the source (periods, amplitudes, and color variations) and shed light on the different time dependencies of various spectral signatures as a result of the modulation of the stellar atmosphere caused by the varying luminosity from low-resolution optical/NIR spectra. We also present a comparative study of the time-dependent spectral variations of the OH/IR star with the classical Mira variables. This paper is organized as follows. The observations and data reduction procedures are presented in Section 2. Section 3 deals with our new results and discussion. The summary and conclusion of our studies are presented in Section 4.

2. Observations and Data Reduction

The optical photometric and spectroscopic observations were carried out using the Hanle Faint Object Spectrograph and Camera (HFOSC) on the 2 m Himalayan Chandra Telescope (HCT) at Hanle, India. The source was monitored in the optical R and I bands over 11 epochs during 2014 August 19–2018 April 17, using a 2K \(\times\) 2K HFOSC imaging CCD (field of view of about 10 \(\times\) 10 arcmin\(^2\)) with a plate scale of 0.296 pixel\(^{-1}\).

For spectroscopy (seven epochs), we have used grism no. 8 (Gr\#8, 580–900 nm) of the instrument with a resolving power of \(\approx2200\).

The NIR photometric observations (one epoch) were acquired using the Near-Infrared Imaging Camera cum Multi-Object Spectrograph (NICMOS-3) on the 1.2 m Mt. Abu telescope, India, and the spectroscopic observations (six epochs) were done using NICMOS-3 and the TIFR Near-Infrared Spectrometer and Imager (TIRSPEC; Ninan et al. 2014) on the 2 m HCT covering 1.5–2.4 \(\mu\)m region. NICMOS-3 has a 256 \(\times\) 256 HgCdTe detector array with a resolution \(R \approx1000\), while TIRSPEC has a 1024 \(\times\) 1024 Hawaii-1 array that provides a resolution of \(\approx1200\). The log of observations is given in Table 1. Photometric observations on 2013 May 28 in the \(JHK\) bands were taken in five dithered positions to generate the NIR sky frame, and multiple frames are taken in each position to get a better signal-to-noise ratio (S/N). In the spectroscopic observing mode, the spectra were taken at two positions dithered by \(\sim10''\) along with the slit to subtract the sky. Several such sets of frames were observed to improve the S/N. The estimated S/N is \(\sim50–80\) in the \(H\) band and \(\sim70–120\) in the \(K\) band for TIRSPEC data, while the S/N is \(\sim30\) in \(H\) and \(K\) for NICMOS-3 data.

The observed data were reduced with the help of standard tasks of the Image Reduction and Analysis Facility (IRAF) following the standard reduction method. The aperture photometry was performed using the APHOT package of IRAF. The zero points of photometry were determined using the standard stars. The time-series \(R\) and \(I\) aperture magnitudes are listed in Table 2. The errors mentioned in Table 2 are purely photometric errors of the object. The systematic errors coming from the standard stars are ignored here. The NICMOS-3 spectroscopic data were analyzed using the APALL task of IRAF. The TIRSPEC data were reduced with TIRSPEC pipeline (Ninan et al. 2014) and was cross-checked with the IRAF reduction method. Both methods of reduction match well. The additional details of the reduction process can be found in Ghosh et al. (2018).

3. Result and Discussion

3.1. Optical Light Curves and Period

The optical light curves in the \(R\) and \(I\) bands are shown in Figure 2, and time-series \(RI\) magnitudes are listed in Table 2.
To estimate the period of the object, we applied the Fourier decomposition technique (Ngeow et al. 2013; Ghosh et al. 2018),

$$m(t) = A_0 + \sum_{k=1}^{N} A_k \sin(\omega t + \phi_k),$$

(1)

where $\omega = 2\pi/P$, $P$ is the period in days, $A_k$ and $\phi_k$ represent the amplitude and phase shift for the $k$th order, respectively, and $N$ is the order of the fit. We fit the light curves considering up to second-order terms of the equation and find the best fit from the $\chi^2$-minimization technique. The best-fit light curve provides a period of $575 \pm 30$ days. The amplitude of variability is $\sim 4.00$ mag in the $R$ band and $\sim 3.5$ mag in the $I$ band. We find that the fall time ($F_f$) of the light curve, 350 days, is greater than the rise time ($R_t$) of 225 days, which indicates the asymmetric behavior of the optical light curves. Such behavior was first noticed by Bowers (1975) in OH-emitting Mira variables. Furthermore, it may appear that there is a phase lag between $R$- and $I$-band light curves. However, this result is inconclusive because of few observations. Note that the

| Date of Observation | Observation Type | Spectral Band | Int. Time (s) | No of Frames | Telescope | Remarks |
|---------------------|-----------------|--------------|--------------|-------------|-----------|---------|
| 2013 May 28 | Spectroscopy | $H/K/K$ | 120/120/120 | 2’ | 1.2 m Mt. Abu | clear sky |
| 2014 Aug 19 | Photometry | $R/I$ | 80/4 | 3/3 | 2 m HCT | clear sky |
| 2015 July 5 | Photometry | $R/I$ | 150/20 | 3/3 | 2 m HCT | clear sky |
| 2015 Nov 19 | Photometry | $R/I$ | 150/20 | 2/2 | 2 m HCT | clear sky |
| 2016 Feb 15 | Photometry | $R/I$ | 100/12 | 3/3 | 2 m HCT | clear sky |
| 2016 May 8 | Photometry | $R/I$ | 100/5 | 3/3 | 2 m HCT | clear sky |
| 2016 Jun 26 | Photometry | $R/I$ | 100/5 | 3/3 | 2 m HCT | clear sky |
| 2016 Nov 2 | Photometry | $R/I$ | 120/7 | 3/3 | 2 m HCT | clear sky |
| 2017 Apr 7 | Photometry | $R/I$ | 60/600 | 2/2 | 2 m HCT | clear sky |
| 2017 Jun 25 | Photometry | $R/I$ | 20/500 | 2/2 | 2 m HCT | clear sky |
| 2018 Apr 17 | Photometry | $R/I$ | 20/400 | 2/2 | 2 m HCT | clear sky |

Log of Photometric and Spectroscopic Observations

| Date of Obs. (UT) | Epoch (JD) | Optical Phase | Telescope/Instrument | $R$ (mag) | $I$ (mag) | $(R - I)$ (mag) |
|-------------------|------------|--------------|----------------------|-----------|-----------|----------------|
| 2014 Aug 19.75    | 2456889    | 0.97         | HCT/HFOSC            | 13.185 ± 0.003 | 10.080 ± 0.002 | 3.105 |
| 2015 July 05.67   | 2457209    | 1.44         | HCT/HFOSC            | 17.416 ± 0.018 | 13.243 ± 0.003 | 4.173 |
| 2015 Oct 06.69    | 2457302    | 1.61         | HCT/HFOSC            | 16.041 ± 0.005 | 13.254 ± 0.004 | 2.787 |
| 2015 Nov 19.55    | 2457346    | 1.70         | HCT/HFOSC            | 15.337 ± 0.007 | 12.336 ± 0.004 | 3.001 |
| 2016 Feb 15.98    | 2457434    | 1.90         | HCT/HFOSC            | 13.346 ± 0.005 | 10.353 ± 0.003 | 2.993 |
| 2016 May 08.83    | 2457517    | 2.05         | HCT/HFOSC            | 13.469 ± 0.009 | 10.369 ± 0.005 | 3.100 |
| 2016 Jun 26.83    | 2457566    | 2.12         | HCT/HFOSC            | 13.854 ± 0.003 | 10.682 ± 0.003 | 3.172 |
| 2016 Nov 02.53    | 2457695    | 2.31         | HCT/HFOSC            | 15.903 ± 0.011 | 12.164 ± 0.003 | 3.739 |
| 2017 Apr 07.92    | 2457851    | 2.55         | HCT/HFOSC            | 16.580 ± 0.007 | 13.350 ± 0.004 | 3.234 |
| 2017 Jun 25.65    | 2457930    | 2.72         | HCT/HFOSC            | 14.936 ± 0.005 | 11.975 ± 0.003 | 2.961 |
| 2018 Apr 17.60    | 2458226    | 3.25         | HCT/HFOSC            | 14.939 ± 0.005 | 11.847 ± 0.004 | 3.092 |

Average: 15.0 11.8 3.2

Table 1

Table 2

Optical $RI$ Photometry
provided optical phases in this paper are derived from the asymmetric light curve as described in van Langevelde et al. (1990) considering phase (Φ) = 0 at 2456329 JD.

The NIR photometric observations were carried out on 2013 May 28.92 UT (Φ ~ 0.16), yielding magnitudes of $J = 6.46 \pm 0.04$ mag, $H = 5.15 \pm 0.05$ mag, and $K = 4.37 \pm 0.04$ mag. The 2MASS $JHK$ measurements (made on 1999 July 23) yield magnitudes of $J = 7.02 \pm 0.03$ mag, $H = 5.47 \pm 0.03$ mag, and $K = 4.52 \pm 0.02$ mag (Cutri et al. 2003). Significant NIR variability is seen only in two epoch observations.

3.2. Distance and Luminosity

We use the period–luminosity (PL) relation of De Beck et al. (2010) based on O-rich Galactic Mira variables to derive the distance to the object. Taking the average of the $K$-band magnitudes over two epochs as described in Section 3.1, the PL relation ($M_K = -3.47(\pm 0.19) \log P + 0.98(\pm 0.45)$) yields the absolute $K$-band magnitude of the source to be $M_K = -8.6 \pm 0.7$ mag. For distance estimation, the relation $m_K - M_K = 5 \log D - 5 + A_K$ is used, where $A_K$ is the interstellar extinction. Considering the Galactic interstellar extinction in the direction toward the source, $A_K = 0.06$ (Schlafly & Finkbeiner 2011), we obtain the distance, $D$, to the source as $4.0 \pm 1.3$ kpc. The uncertainties in the distance measurement come from the uncertainty of the estimated period, PL relation, and photometric error when calculating the $K$-band magnitude. However, the strong variability in the $K$ band and the circumstellar extinction of heavily obscured sources are the main constraints to this method of determining the distance of OH/IR star (De Beck et al. 2010). We have found that the derived distance based on the PL relation is consistent with the distance (~5.0 kpc) estimated by Anders et al. (2019) using the Gaia DR2 parallax measurement (Gaia Collaboration et al. 2018) and photometric catalogs.

We have also estimated the bolometric magnitude $M_{bol}$ using the PL relation ($M_{bol} = -1.85(\pm 0.24) - 2.55(\pm 0.10) \log P$) of Whitelock et al. (1991). The relation provides the bolometric magnitude of $M_{bol} = -5.19 \pm 0.38$ corresponding to the luminosity ~9500 $L_{\odot}$ (taking the solar bolometric magnitude $M_{bol,\odot} = 4.75$ mag from De Beck et al. 2010).

3.3. Spectral Energy Distribution

To fit the SED, we have adopted the radiative transfer code, More of Dusty’ (MoD; Groenewegen 2012), which considers a slightly updated and modified version of the “DUSTY” code version, 2.01 (Ivezic et al. 1999), as a subroutine within a minimization code. The MoD works to find best-fit parameters, e.g., luminosity ($L$), dust optical depth at $0.55 \mu m$ ($\tau_{0.55}$), dust temperature at the inner radius ($T_c$) and slope, $p$, of the density distribution ($\rho \sim r^{-p}$) by using photometric, spectroscopic, and visibility data as well as one-dimensional intensity profiles in the minimization process. Here, we consider photometric and spectroscopic data as the data of the latter two are unavailable in the literature.

For photometric and spectroscopic data, we made use of the broadband optical $I$ band to far-infrared (FIR) multiwavelength data and IRAS-LRS spectra. The fluxes, used here for the SED fit, are obtained from the archival Two Micron All Sky Survey (2MASS; Cutri et al. 2003) at 1.23, 1.66, and 2.16 $\mu m$; the AllWISE Data Release (Cutri et al. 2013) at 3.35, 4.6, 11.6, and 22.1 $\mu m$; the AKARI/IRC all-sky Survey (ISAS/JAXA 2010; Ishihara et al. 2010; Yamamura et al. 2010) at 8.61, 18.4, and 90 $\mu m$; and IRAS catalog of Point Sources (IPAC 1986) at 12, 25, and 60 $\mu m$ as listed in Table 3. The coordinates in the AKARI/FIS Bright Source Catalog are 5.05’ away from the source coordinates as listed in Table 3. However, the position accuracy of 60” is recommended for all sources in the catalog for a practical and safe value (Yamamura et al. 2010). We also included our three epochs’ (at the maximum, minimum, and middle of the light curve) $I$-band variability data and one epoch’s $JHK$ measurements in our calculation. The observed $I$ and $JHK'$ magnitudes are converted to flux densities using the zero magnitudes for Vega, as described in Groenewegen (2006). The IRAS-LRS spectrum was taken from the database maintained by Kevin Volk. In general, the errors of the spectroscopic fluxes are scaled typically by a factor of 0.2, to provide roughly equal weight in the photometric and spectroscopic data to the overall data set (Blommaert et al. 2018). The quality of the fit is obtained through a $\chi^2$ analysis.

Input to MoD is a master input file containing the interstellar reddening ($A_V = 0.65$; Schlegel et al. 1998), the distance ($D = 4.0$ kpc), the path to the file containing the absorption and scattering coefficients of the dust, the path to the file containing the spectrum of the central star, the effective temperature, the number of shells ($N = 1$, i.e., one-shell model), the outer radius (set to 2000 times the inner radius), and the scaling factors (s(N), set to 1). Finally, initial guesses of the fit parameters ($L$, $\tau_{0.55}$, $T_c$, $p$) and a code whether these parameters should be varied or fixed (Groenewegen 2012 for details) are provided. The MARCS hydrostatic model atmosphere (Gustafsson et al. 2008) of 2600 K (and $g = 0.0$, $1 \, M_{\odot}$, and solar metallicity) is used for the spectra of the central stars. The dust species are taken as a mixture of $Mg_0.8Fe_{2.5}SiO_4:AlO:Fe = 100:0:10$, calculated using the distribution of hollow spheres with mean grain size $a = 0.2 \mu m$ and a maximum volume fraction of a vacuum core $f_{max} = 0.7 \mu m$. Here, $T_c$ and $p$ have been fixed to 1100 K and 2, respectively, only fitting for $L$ and $\tau_{0.55}$.

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*Figure 2. Optical light curves of IRAS 18278+0931 in the $R$ band (top) and $I$ band (bottom), where the filled circles are our observed data points, while the dashed lines are the fitted light curves with $P = 575$ days. The vertical lines are marked on the maximum and minimum light positions to show the different rise and fall times.*
The MoD fit SED is shown in Figure 3. The $\chi^2 (\chi^2_{\text{red}} = 865)$ of the fit is typically large as the object is a large-amplitude variable and owing to the nonsimultaneous taking of the photometric data from different catalogs. The provided errors are therefore internal errors scaled to a reduced $\chi^2$ of 1. The MoD fit SED provides the resulting parameter, $L = 9600 \pm 500L_\odot$, that is comparable to our PL-based estimation, $r_0 = 9.1 \pm 0.6$, inner radius ($R_{\text{in}} = 5.4 R_{\text{star}}$, MLR ($M_L = 1.0 \times 10^{-6} M_\odot$ yr$^{-1}$), and grain density ($\rho = 2.65$ g cm$^{-3}$). $M_L$ is estimated by assuming a 10 km s$^{-1}$ expansion velocity and a dust-to-gas ratio of 0.005. The derived MLR is a factor of 4 lower than the value ($3.95 \times 10^{-6} M_\odot$ yr$^{-1}$) that is evaluated by applying the relation 

$$\log(M) = -7.37 + 3.42 \times 10^{-3} \times P$$

provided by De Beck et al. (2010) for periods shorter than 850 days. However, considering the large scatter (up to a factor of 10) around the relation in De Beck et al. (2010), we can conclude that the derived values of the MLR are in reasonable agreement. Furthermore, the derived MLR appears to be on the low side for an OH/IR star. The low MLR of the OH/IR star likely implies that the star does not evolve to the superwind phase, a phase with the highest MLRs toward the tip of the AGB (Iben & Renzini 1983).

To check how changes in $T_c$ and distance are affecting the output parameters, we change the $T_c$ by 100 K and the distance by 1 kpc. A change in $T_c$ by 100 K changes the derived luminosity by 10%, optical depth by 6%, and MLR by 12%. A change in the distance from 4.0 kpc to 3.0 kpc changes the luminosity by 10%, optical depth by 6%, and MLR by 12%. A change in the luminosity or optical depth, do not reflect the uncertainty connected to the distance.

Using the distance ($\sim$5.0 kpc) provided by the PL relation based on O-rich Mira variables in the LMC (for example, Ita & Matsunaga 2011; Yuan et al. 2017), the $L$ obtained from the modeling is a factor of $\sim$1.6 larger than the luminosity obtained from the Galactic PL relation of Whitelock et al. (1991). This is because of the overestimation of the distance, and thus, the derived distance to the Galactic OH/IR star from the LMC PL relation needs to be considered carefully.

The model-estimated luminosity, $9600 \pm 500L_\odot$, is consistent with the Whitelock et al. (1991) PL relation-based estimation as described in Section 3.2. We noticed that some of the PL relations (for example, the PL relation from Hughes & Wood 1990; Ita & Matsunaga 2011) overestimate the luminosity.
3.4. Galactic Location and Current Mass

Following Jura & Kleinmann (1992), the estimated \(z\)-scale height of the object, \(\sim 230 \text{ pc}\), suggests a thin-disk population (Habing 1988; Jura & Kleinmann 1992; Jurić et al. 2008). The bulge population could be ruled out from the IRAS color criteria (\(1 < f_\nu(12) < 5 \text{ Jy}, \ 0.5 < f_\nu(12)/f_\nu(25) < 1.5\), where \(f_\nu(12)\) is the flux density at 12 \(\mu\text{m}\); Habing et al. 1985). We thus conclude that our object is an OH/IR star in the Galactic thin disk. Following the mass–luminosity relation in Figure 6 of Hughes & Wood (1990), the object with \(P = 575\) days and \(M_{\text{bol}} = -5.19\) lies in the mass \((M)\) range of 1–1.5 \(M_\odot\). Furthermore, the luminosity of our source as estimated in Section 3.3 indicates that it belongs to the “high-luminosity group.” For the “high-luminosity group,” the main-sequence progenitor masses are in the range of 4 \(M_\odot\) to 6 \(M_\odot\) (Jiménez-Esteban & Engels 2015). Comparing the current mass of our source to the estimated mass range of the progenitor, one concludes from the MLR that it has lost mass of 3–5 \(M_\odot\) in a mere 3–5 Myr.

3.5. Optical/NIR Spectroscopic Studies

The optical and NIR spectra of the object with variability phases are shown in Figures 4 and 5, respectively. The spectra show several atomic or/and molecular features as commonly seen in late-type O-rich stars (e.g., Castelaz et al. 2000; Lançon & Wood 2000; Ghosh et al. 2018). A comparison by eye shows that all of the optical spectra of the object resemble O-rich spectral types later than M6.

It is found that the two ends of the \(H\) and \(K\) spectra bend downwards due to broad \(\text{H}_2\text{O}\) absorption features centered at 1.4, 1.9, and 2.7 \(\mu\text{m}\), indicating the overall change of the
3.5.1. Phase-dependent Spectral Variability and Comparison with Miras

Time-series spectra are obtained to study the variability of the spectra and to understand the dynamical atmosphere because of the stellar pulsation. For that, we explore the pulsation-related variations of some of the important spectral features. We estimate different indices and equivalent widths (EWs) of selected features using continuum bands and feature bands as listed in Table 4. We follow the method as described in Ghosh et al. (2019) using the IDL script9 (Newton et al. 2014) for EW estimation. To compare the spectral behavior between long-period variables having a different period, we overplot the same indices, estimated from multiepoch spectra of S Car (P = 149 days), RS Hya (P = 339 days), and MASTER OT J212444.87+321738.3 (P = 465 days) as illustrated in Figure 6. The spectra of those Mira variables are taken from Lançon & Wood (2000; S Car and RS Hya) and Ghosh et al. (2018; MASTER OT J212444.87+321738.3).

We explore the optical phase variation of the [TiO] index centered at 7100 Å (O’Connell 1973), the [TiO] index of triple-headed absorption bands at 8433, 8442, and 8452 Å (Zhu et al. 1999), and the flux ratio (S2/3,Sp) of two strong absorption bands, 770–807 and 829–857 nm (see Figure 4), that is actually related to the spectral type of static giants (Fluks et al. 1994). While the [TiO] index shows a small variation with the pulsation phase and increases as the visual brightness decreases, the [TiO] index and S2/3,Sp show no significant variation, indicating the saturation of the TiO bands. However,

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9 https://github.com/ernewton/nirew

Figure 5. The NIR HK-band spectra of IRAS 18278+0931 in the wavelength range 1.50–2.40 μm at six different phases are shown in the upper and lower panels, respectively. The NIR spectra at the bottom (phase ~0.16) are taken with the NICMOS-3 instrument on the 1.2 m Mt. Abu telescope, and the rest are observed with the TIRSPEC instrument on the 2.0 m HCT. The H-band spectra in the wavelength range 1.52–1.80 μm show four strong 12CO second-overtone bands including several OH lines. In the K-band spectra, the 13CO first-overtone bands are the dominant features in the spectra, and Na I, Ca I, and Mg I are seen at 2.20 μm, 2.26 μm, and 2.28 μm, respectively. The spectra have been normalized to unity at 16500 Å (H band) and 21700 Å (K band), and offset by a constant value of 0.30 with respect to the bottom spectra in the same panel.
the VO band (see Figure 4) also contributes toward the [TiO]₃ index measurement, and a small change in the [TiO]₃ index with phase can be due to the change in VO band strength.

We have estimated the EWs of Na I (2.20 μm), Ca I (2.26 μm), Mg I at 2.28 μm, and CO bands (¹²CO at 1.58, 1.62, 2.29, and 2.32 μm) as described above, and the H₂O-H₂ and H₂O-K₂ indices following Ghosh et al. (2018) and Rojas-Ayala et al. (2012), respectively. All of the indices vary significantly over the phase except CO as shown in Figure 6. The minimum of the metal lines (except Mg I) and CO absorption occurs around phase 0.7, i.e., shortly after minimum light (see Figure 6), which may be attributed to the line blurring and veiling (Merrill 1940; Lançon & Wood 2000).

Furthermore, a clear change in the line shape of the CO overtone band heads with phase is presented in Figure 7. The reason for the line shape variation is the velocity stratification, due to the presence of shock (Hinkle & Barnes 1979; Nowotny et al. 2010). The appearance of such a variability in our low-resolution spectra (Figure 7) is due to the modification of the combined shape of several unresolved individual lines. However, our low-resolution spectra limit the investigation of line doubling and the detail change in velocity profile as discussed earlier (Hinkle & Barnes 1979; Nowotny et al. 2010).

A significant variation of the spectral indices over the phase is evident for individual stars. However, a comparison of these indices among multiple AGB stars yields no unique variation with phase, except possibly Mg I and water indices. Such different behaviors from star to star might be because of their different instantaneous atmospheric structure during pulsation, which makes it difficult to explain the cause of the different variabilities for any spectral feature. Also, a more

Table 4
Definitions of Spectral Bands

| Feature       | Bandpass (μm)            | Continuum Bandpass (μm) | References                      |
|---------------|--------------------------|------------------------|---------------------------------|
| [TiO]₃        | 0.8455–0.8725            | 0.8390–0.8410, 0.8700–0.8725 | 1                               |
| Na I (2.21 μm)| 2.2040–2.2107            | 2.1910–2.1966, 2.2125–2.2170 | 2                               |
| Ca I (2.26 μm)| 2.2577–2.2692            | 2.2450–2.2560, 2.2700–2.2720 | 2                               |
| Mg I (2.28 μm)| 2.2795–2.2845            | 2.2700–2.2720, 2.2850–2.2874 | 3                               |
| ¹²CO (1.58 μm)| 1.5752–1.5812            | 1.5705–1.5745, 1.5830–1.5870 | 4                               |
| ¹²CO (1.62 μm)| 1.6175–1.6220            | 1.6145–1.6175, 1.6255–1.6285 | 5                               |
| ¹²CO (2.29 μm)| 2.2910–2.3020            | 2.24200–2.2580, 2.2840–2.2910 | 4                               |
| ¹²CO (2.32 μm)| 2.3218–2.3272            | 2.2325–2.2345, 2.2695–2.2715 | 4                               |

References. (1) Zhu et al. (1999); (2) Frogel et al. (2001); (3) Silva et al. (2008); (4) Ghosh et al. (2019); (5) Silva et al. (2008).
Table 5
Phase-dependent Variation of the Spectral Features

| Date of Obs. | Optical Phase | [TiO$_3$] Index | $S_{2/3,Sp}$ | CO 4–1 | CO 6–3 | H$_2$O-H$_4$ Index | Na I 2.20 $\mu$m | Ca I 2.26 $\mu$m | Mg I 2.26 $\mu$m | CO 2–0 | CO 3–1 | H$_2$O-K2 Index | Sp. Type$^a$ |
|--------------|--------------|-----------------|-------------|--------|--------|------------------|----------------|----------------|----------------|--------|--------|----------------|------------|
| 2013 May 28.92 | 0.16          | …               | …           | 2.15 ± 0.41 | 3.86 ± 0.73 | 0.59 ± 0.01 | 4.27 ± 0.47 | 0.08 ± 0.21 | 0.77 ± 0.24 | 30.17 ± 3.61 | 15.85 ± 2.02 | … | … |
| 2013 Oct 15.52 | 0.36          | 0.99 ± 0.05     | 0.289 ± 0.007 | …       | …       | …               | …               | …               | …               | …     | …     | …             | M8        |
| 2013 Nov 07.57 | 0.39          | 0.99 ± 0.06     | 0.330 ± 0.003 | …       | …       | …               | …               | …               | …               | …     | …     | …             | M8        |
| 2014 Aug 19.75 | 0.96          | 0.87 ± 0.04     | 0.398 ± 0.006 | …       | …       | …               | …               | …               | …               | …     | …     | …             | M7        |
| 2014 Oct 29.54 | 1.08          | …               | …           | 3.18 ± 0.44 | 2.83 ± 0.29 | 0.64 ± 0.01 | 4.01 ± 0.66 | 4.09 ± 0.38 | 0.12 ± 0.09 | 28.80 ± 2.72 | 12.05 ± 1.83 | 0.60 ± 0.01 | … |
| 2015 Mar 02.93 | 1.26          | 0.93 ± 0.09     | 0.387 ± 0.003 | 1.95 ± 0.28 | 3.39 ± 0.49 | 0.39 ± 0.01 | 2.21 ± 0.35 | 1.94 ± 0.21 | 0.44 ± 0.13 | 29.12 ± 3.19 | 16.10 ± 1.91 | 0.45 ± 0.01 | M7.5 |
| 2015 July 05.67 | 1.43          | 1.01 ± 0.04     | 0.401 ± 0.007 | …       | …       | …               | …               | …               | …               | …     | …     | …             | … |
| 2015 Oct 07.69 | 1.61          | 0.91 ± 0.04     | 0.362 ± 0.005 | 1.15 ± 0.36 | 2.89 ± 0.28 | 0.27 ± 0.01 | 0.10 ± 0.17 | -0.12 ± 0.15 | 1.96 ± 0.31 | 16.85 ± 1.71 | 14.91 ± 1.23 | 0.40 ± 0.01 | M7.5 |
| 2015 Nov 20.55 | 1.70          | …               | …           | 0.57 ± 0.17 | 0.78 ± 0.12 | 0.29 ± 0.01 | -0.70 ± 0.16 | -0.49 ± 0.12 | 1.06 ± 0.24 | 21.36 ± 1.97 | 14.97 ± 1.75 | 0.48 ± 0.01 | … |
| 2016 Feb 15.98 | 1.90          | 0.76 ± 0.05     | 0.527 ± 0.005 | …       | …       | …               | …               | …               | …               | …     | …     | …             | M7        |
| 2017 Apr 07.92 | 2.55          | …               | …           | 1.16 ± 0.29 | 0.94 ± 0.19 | 0.25 ± 0.01 | -0.34 ± 0.14 | 0.30 ± 0.08 | 1.58 ± 0.37 | 26.27 ± 2.81 | 14.73 ± 2.14 | 0.38 ± 0.01 | … |

Note.

$^a$ The spectral type has been estimated using the correlation with the [TiO$_3$] Index.
complete phase coverage of the pulsation cycle is needed to clarify the correlations.

We estimate the spectral type (ST) of the OH/IR star quantitatively at different variability phases using the correlation between the ST and [TiO]$_3$ index ([TiO] at 8450 Å) as in Zhu et al. (1999). The estimated STs at different phases are shown in Table 5. The ST of the object varies from M7 to M8 over the phase of the pulsation cycle in our limited phase coverage. However, we could not see the large ST variation over the pulsation, which is expected for this kind of long-period, large-amplitude, variable stars because of the saturation of the [TiO]$_3$ index.

4. Summary and Conclusion

We have characterized the time-dependent properties of the OH/IR star IRAS 18278+0931 using long-term optical/NIR photometric and spectroscopic observations. Our main results are summarized as follows.

1. We have estimated the variability period of $575 \pm 30$ days from the best-fit of the optical $R$ and $I$ band light curves with wavelength-dependent variability amplitudes of $\Delta R \sim 4.0$ and $\Delta I \sim 3.5$ mag. From the PL relation, the distance to the source is estimated to be $4.0 \pm 1.3$ kpc, which is also consistent with the distance derived from the Gaia parallax.

2. Using a DUSTY-based MoD, we have fitted the optical to FIR photometric data and LRS-IRAS spectral data to construct the SED. The best-fit SED gives (a) a luminosity of $9600 \pm 500 L_\odot$ for our source, which is in good agreement with the value derived from the PL relation, (b) and an optical depth of $9.1 \pm 0.6$ at 0.55 µm, and (c) an MLR of $1.0 \times 10^{-6} M_\odot \text{yr}^{-1}$. The MLR is also comparable to the estimated value from the period–MLR relation. The current mass of the object lies in the range of $1-1.5 M_\odot$. Furthermore, the estimated luminosity of our source indicates that it belongs to the “high-luminosity group.” Comparing the current mass of the source to the mass range ($4-6 M_\odot$) of the progenitors for the “high-luminosity group,” one concludes that it has lost mass of $3-5 M_\odot$ in a mere 3–5 Myr.

3. The spectra of the object at different variable phases, covering the optical range from 0.6 to 0.9 µm and NIR range from 1.5 to 2.4 µm, are studied. Notable variations in spectral features in all atomic and molecular lines (e.g., TiO, Na I, Ca I, and Mg I) over phases are seen, illustrating the sensitivity of the spectral features to the dynamical atmosphere of the pulsating object. Furthermore, different lines behave differently, signifying their origin in various depths of the very extended atmosphere.

4. A comparative time-series spectral study between the Mira variables and OH/IR star indicates a possible correlation between the index and the phase for the individual stars; however, they show a large dispersion. No unique correlation is seen between spectral indices and the phase, except possibly Mg I and water indices. A complete phase coverage of the pulsation cycle would help to clarify the correlations.

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**Software:** IRAF (Tody 1986, 1993), TIRSPEC pipeline (Ninan et al. 2014), More of Dusty (MoD; Groenewegen 2012), DUSTY (Ivezic & Elitzur 1997).
