ISO Observations of the Planetary Nebula Lindsay 305 in the Small Magellanic Cloud*

Arūnas KUČINSKAS,1,2,3 Vladas VANSEVIČIUS,4 Marc SAUVAGE,5 and Toshihiko TANABE6

1National Astronomical Observatory, Mitaka, Tokyo 181-8588
2Institute of Theoretical Physics and Astronomy, Vilnius 2600, Lithuania
3Institute of Material Research and Applied Science, Vilnius University, Vilnius 2009, Lithuania
4Institute of Physics, Vilnius 2600, Lithuania
5CEA/DSM/DAPNIA/Service d’Astrophys., C. E. Saclay, F-91191 Gif-sur-Yvette Cedex, France
6Institute of Astronomy, School of Science, The University of Tokyo, Mitaka, Tokyo 181-0015

E-mail (AK): arunaskc@cc.nao.ac.jp

(Received 2000 January 27; accepted 2000 March 16)

Abstract

We present ISO (Infrared Space Observatory) observations of the planetary nebula Lindsay 305 (L 305) in the Small Magellanic Cloud. L 305 is very prominent in the ISOCAM frames at 6.75 and 11.5 μm, although it is under the detection limit at 4.5 μm. The obtained spectral energy distribution shows a strong mid-IR excess, which, depending on the amount of energy radiated at wavelengths longer than 11.5 μm, may be as large as ~ 1500 L⊙. However, since an accurate estimate of the total nebular luminosity is not available to date, the evolutionary status of L 305 can not yet be constrained precisely.

Key words: infrared: stars — Magellanic Clouds: SMC — planetary nebulae: individual (Lindsay 305) — space vehicles: ISO satellite — stars: AGB and post-AGB — stars: evolution

1. Introduction

Lindsay 305 (L 305, Lindsay 1961; SMP 21, Sanduleak et al. 1978) is a planetary nebula located in the vicinity of the young populous cluster NGC 330 in the Small Magellanic Cloud (SMC). The optical spectrum of L 305 displays abundant forbidden emission lines typical of planetary nebulae ([OIII], [NeV], [NeIII], [NII] etc. — see e.g., Monk et al. 1988). Monk et al. (1988) and Leisy and Dennefeld (1996) have classified L 305 as a Type I planetary nebula, whereas the central object of the nebula has been suspected to be a binary system (Leisy, Dennefeld 1996). Recent Hubble Space Telescope (HST) Faint Object Camera (FOC) imaging has revealed a noticeable asymmetry of L 305 (Vassiliadis et al. 1998, hereafter V98; Stanghellini et al. 1999, hereafter S99).

The evolutionary status of L 305 is rather unclear. The dynamical age estimates obtained by V98 and S99 from HST imaging differ by more than a factor of 5, and hence do not allow one to set out a reliable age estimate of L 305 (see section 3). However, if the luminosity and effective temperature of the central star of the nebula is known, a comparison of these parameters with the theoretical models of post-AGB evolution may yield an independent estimate of the nebular age.

It is well known, however, that planetary nebulae are surrounded by dust envelopes, which produce strong excess at the mid-infrared (mid-IR) wavelengths (e.g., Pottasch 1997). Any reliable luminosity estimate should therefore account adequately for the amount of energy emitted in the infrared. Thus, the mid-IR observations would help to constrain the total amount of energy emitted by the nebula (and thus the luminosity of the central star) and would allow one to further clarify the evolutionary status of L 305.

In this work we present ISOCAM observations of L 305. Since no previous observations of L 305 at mid-IR wavelengths are available, our data offers the first possibility of probing the dusty envelope of this nebula. Combining our data with the observations available from the literature we briefly discuss the evolutionary status of L 305.

2. Observations and Results

The planetary nebula L 305 was observed during the course of raster imaging observations of the populous cluster NGC 330 with the ISOCAM (Cesarsky et al.

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the F1 countries: France, Germany, the Netherlands, and the United Kingdom) and with the participation of ISAS and NASA.
† Research Fellow of the Japan Society for the Promotion of Science.
1. Identification chart of L 305 in $I$-band (north is up and east is left). Part of the SMC populous cluster NGC 330 is seen at the lower right. The insert shows a HST FOC [O iii] $\lambda$ 500.7 nm image of L 305 taken from V98 (scale is 1" on each side of the insert box).

Observations were made on 1997 May 22 using broadband CAM filters (LW 1, LW 2, and LW 10, corresponding to the effective wavelengths of 4.5, 6.75, and 11.5 $\mu$m, respectively) with a pixel field of view (PFOV) of 3". The raster mode was 5 x 5, with the raster step size equal to 8 pixels (24""). The fundamental integration time was set to $t_{int} = 2.1$ s, with a total number of 15 exposures per single raster position.

ISOCAM data were reduced using CAM Interactive Analysis software, CIA version 3.0 (The ISOCAM data presented in this paper was analyzed using “CIA”, a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C. E. A., France). Photometry was performed with the IRAF AP-PHOT package. The obtained ISOCAM fluxes are equal to 1.2 mJy and 5.5 mJy at LW 2 and LW 10, respectively. Since L 305 was not detected at 4.5 $\mu$m, our data yields only an upper limit estimate of < 0.5 mJy at this wavelength. The absolute photometric uncertainty of our measurements comes mainly from the ISOCAM calibration uncertainties and a correction for the memory effect (transient) of the ISOCAM, which is estimated to be less than 20% (Biviano 1998).

The optical counterpart of the infrared source was identified from the instrumental coordinates of L 305, which were derived with respect to the relative positions of 8 field stars on LW 10 CAM frame (identification accuracy is ~ 1"). An optical identification chart of L 305 is shown in figure 1.

3. Discussion

Currently available observational and theoretical data provide quite a diverse view of the evolutionary status of L 305. Photoionization models (Dopita, Maetheringham 1991) give $T_{\text{eff}} = 95,000$ K and $L_* = 1750 L_\odot$ for the central ionizing source. Together with the theoretical tracks of post-AGB evolution, these parameters yield a main-sequence mass of $1.0 M_\odot$ and $1.4 M_\odot$ for the He and H burning central star, respectively (Vassiliadis, Wood 1994). A direct estimate of dynamical age of the envelope (based on the [O III] $\lambda$ 500.7 nm narrow-band images taken with the FOC on board the HST, and expansion velocities derived from the spectral observations of the same line) gives $\tau_{\text{dyn}} = 21,400$ yr (S99). These facts quite consistently indicate that L 305 should be an evolved planetary nebula.

However, at least two arguments work against the evolved dynamical status of L 305. First, the dynamical age derived by V98 (obtained using the same HST FOC image and [O III] spectral data as in S99) is much smaller, i.e., $\tau_{\text{dyn}} \sim 2500$ yr and $\tau_{\text{dyn}} \sim 4000$ yr for the He-burning and H-burning central star scenarios, respectively. Second, the high electron density ($4 \times 10^4$ cm$^{-3}$, ...
Monk et al. 1988; 10⁴ cm⁻³; Leisy, Dennefeld 1996) and small nebular size of L 305 also suggest a young dynamical age.

Indeed, an estimate of the dynamical age is strongly dependent upon the nebular geometry, the method used to determine the nebular expansion velocity and so forth. The expansion velocity, as measured by V98, was defined at the 10% level of the maximum line intensity, and therefore probed the fastest moving material of the nebula (yielding the expansion velocity of \( v_{\exp} = 35.2 \) km s⁻¹). S99, however, has defined the expansion velocity at the full width at half-maximum (FWHM) of the line, obtaining \( v_{\exp} = 19.3 \) km s⁻¹. Therefore, the dynamical age obtained by V98 should be systematically smaller than that obtained by S99 by a factor of ~ 2. This, however, still can not account for the surprisingly large difference between the dynamical ages derived by S99 and V98. One of the possibilities to discriminate between these age estimates is to make a comparison between the evolutionary parameters of L 305 derived from the dynamical age estimates mentioned above and those obtained by other methods.

If the effective temperature of the central object is known, the dynamical age combined with the theoretical models of stellar evolution can provide a luminosity estimate of the central star. Employing theoretical models of the post-AGB evolution of Vassiliadis and Wood (1994) and assuming that the effective temperature of the central object is 95,000 K (Dopita, Maetheringham 1991) one obtains \( \sim 8000 L_\odot \) and \( \sim 3500 L_\odot \) for the dynamical ages of V98 and S99, respectively. Both of these estimates are considerably larger than 1750 \( L_\odot \) predicted by Dopita and Maetheringham (1991) from the photoionization models.

The discrepancy between these luminosity estimates may be due to the fact that the luminosity of the central object derived by Dopita and Maetheringham (1991) was obtained assuming that the extinction towards L 305 was equal to zero. However, at least several independent studies show that the extinction towards L 305 is non-negligible. The reddening constant at H\( \beta \), c(H\( \beta \)) [the definition of which comes from \( I_{\text{corr}}(\lambda)/I_{\text{corr}}(H\beta) = I_{\text{obs}}(\lambda)/I_{\text{obs}}(H\beta) \times 10^c(H\beta)f(\lambda) \)], where \( I_{\text{obs}}(\lambda) \) and \( I_{\text{corr}}(\lambda) \) are observed and corrected intensities at wavelength \( \lambda \) and \( f(\lambda) \) is the reddening curve, as parametrized by Miller and Mathews (1972) was found to be 0.79 and 0.44 by Monk et al. (1988) and Leisy and Dennefeld (1996), respectively. If we crudely assume that the flux in H\( \beta \) is directly proportional to stellar luminosity (e.g., Kaler 1970) and take the averaged reddening constant to be ~ 0.6, we will find that the luminosity of the central object in L 305 may be underestimated up to by a factor of ~ 4, if the reddening is neglected. The corrected luminosity (~ 7000 \( L_\odot \)) would imply an evolutionary age of ~ 4200 yr for the H-burning central star (Vassiliadis, Wood 1994), which would be in good agreement with the direct estimate obtained by V98 (~ 4000 yr).

The interstellar reddening towards NGC 330 is small and covers the range from \( E(B-V) = 0.03 \) (Carney et al. 1985) to \( E(B-V) = 0.12 \) (Bessell 1991). Therefore, the high reddening discussed by Monk et al. (1988) and Leisy and Dennefeld (1996) should be of circumstellar origin. However, if the reddening is caused by circumstellar extinction in the dust envelope surrounding the nebula, the absorbed radiation should be re-emitted at longer wavelengths. Indeed, the spectral energy distribution of L 305 (figure 2) shows a prominent excess in the mid-infrared (\( \lambda \geq 7 \mu\text{m} \)), which can be due to thermal emission by circumstellar dust. A simple estimate (obtained by integration over the blackbody fit of the observed mid-infrared fluxes) shows that the amount of energy emitted in the infrared is \( L_{\text{IR}} \approx 250 L_\odot \). This is obviously too low to account for the difference between 1750 \( L_\odot \) obtained by Dopita and Maetheringham (1991) and ~ 7000 \( L_\odot \) predicted from the reddening considerations above.
Indeed, at the dust temperatures typical for the planetary nebulae, ~ 100–250 K (see e.g., Tajitsu, Tamura 1998), the largest fraction of energy will be re-emitted by dust at wavelengths longer than ~ 12 µm. Using a sample of planetary nebulae studied by Zhang and Kwok (1991) as an example, we estimate that the total amount of energy emitted in the infrared is typically 4–5 times greater than the amount of energy estimated from the blackbody fit to the mid-IR data (λ = 7–12 µm). Thus, the total infrared luminosity of L 305 could be considerably larger, i.e., reaching $L_{\text{IR}} \sim 1000–1500 L_\odot$. Together with $\sim 1750 L_\odot$ obtained by Dopita and Maetheringham (1991), this would come close to $\sim 3500 L_\odot$ (implied from the dynamical age estimate of S99), giving support for a low-mass evolved nebula scenario.

It should be stressed, however, that due to the complicated geometries of the planetary nebulae, a considerable amount of stellar photons can escape without affecting the nebula, itself. In such a case, the total luminosity of L 305 would be considerably higher than the luminosity estimate obtained by Dopita and Maetheringham (1991) and corrected for the amount of energy re-radiated at the mid-IR wavelengths. However, the fraction of photons escaping the nebula is not known in the case of L 305. Therefore, in view of this argument (and other contradictory facts mentioned above), it still seems impossible to derive a precise luminosity estimate for L 305. Hence, even though our results point to a low-mass evolved nebula scenario, the evolutionary status of L 305 still needs to be clarified by future observations made in the UV, near-IR, and far-IR wavelengths backed up by a comprehensive self-consistent theoretical model of L 305.

4. Conclusions

We present ISOCAM observations of the planetary nebula L 305 located in the vicinity of the young populous cluster NGC 330 in the Small Magellanic Cloud. Previous observations of this object have given quite a diverse view on the evolutionary status of L 305, indicating that it may be either a dynamically young planetary nebula with a high-mass central object, or a rather evolved nebula with a low-mass central star. Our observations have revealed that L 305 shows a strong excess in the mid-IR. We estimate that, depending on the amount of radiation emitted at wavelengths longer than 11.5 µm, the total infrared luminosity can be as high as $\sim 1500 L_\odot$. However, the presently available observations do not allow us to derive a precise estimate of the total luminosity of the nebula. Therefore, even though our results would support a low-mass evolved nebula scenario, the evolutionary status of L 305 still remains to be constrained by future studies.

We thank an anonymous referee for valuable comments and suggestions, and Yollande McLean for a careful reading of the manuscript. This research was supported in part by grant-in-aids for Scientific Research (C) and for International Scientific Research (Joint Research) from the Ministry of Education, Science, Sports and Culture in Japan.

References

Balona L.A. 1992, MNRAS 256, 425
Bessell M.S. 1991, in IAU Symp. 148, The Magellanic Clouds, ed R. Haynes, D. Milne (Kluwer, Dordrecht) p 273
Biviano A. 1998, in The ISOCAM Calibration Error Budget Report, version 3.1, p16 www.iso.vilspa.esa.es/users/exp.lib/performance.html
Carney B.W., Janes K.A., Flower P.J. 1985, AJ 90, 1196
Cesarsky C.J., Abergel A., Agnese P., Altieri B., Augères J.L., Aussel H., Biviano A., Blommaert J. et al. 1996, A&A 315, L32
Dopita M.A., Maetheringham S.J. 1991, ApJ 367, 115
Kaler J.B. 1976, ApJ 210, 843
Keller S.C., Wood P.R., Bessell M.S. 1999, A&AS 134, 489
Kessler M.F., Steinz J.A., Anderegg M.E., Clavel J., Drechsel G., Estaria P., Faelker J., Riedinger J.R. et al. 1996, A&A 315, L27
Leisy P., Dennefeld M. 1996, A&AS 116, 95
Lindsay E.M. 1961, AJ 66, 169
Miller J.S., Mathews W.G. 1972, ApJ 172, 593
Monk D.J., Barlow M.J., Clegg R.E.S. 1988, MNRAS 234, 583
Pottasch S.R. 1997, in Planetary Nebulae, ed H.J. Habing, H.J.G.L.M. Lamers (Kluwer, Dordrecht) p483
Sanduleak N., MacConnell D.J., Philip A.G.D. 1978, PASP 90, 621
Stanghellini L., Blades J.C., Osmer S.J., Barlow M.J., Liu X.-W. 1999, ApJ 510, 687 (S99)
Tajitsu A., Tamura S. 1998, AJ 115, 1989
Vallenari A., Ortolani S., Chiosi C. 1994, A&AS 108, 571
Vassiliadis E., Dopita M.A., Maetheringham S.J., Bohlin R.C., Ford H.C., Harrington J.F., Wood P.R., Stecher T.P., Maran S.P. 1998, ApJ 503, 253 (V98)
Vassiliadis E., Wood P.R. 1994, ApJS 92, 125
Zhang C.Y., Kwok S. 1991, A&A 250, 179