The interaction of a stellar wind with the ISM: The interstellar environments of WR stars

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THE INTERACTION OF A STELLAR WIND WITH THE ISM: THE INTERSTELLAR ENVIRONMENTS OF WR STARS

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Starting with a short summary of the modern understanding of the stellar wind effects on the ISM, we consider new data based on an emission-line imaging survey of the WR star population in the Magellanic Clouds (Dopita *et al.*, 1994) and Radio and IRAS Observations of Two Nebulae Around WO Stars: G2.4+1.4 in the Galaxy and Sandage No. 3 in IC 1613 (Goss and Lozinskaya, 1995).

The name of S. B. Pikelner is connected with the problem of stellar wind action on the ISM more than with other problems of modern astrophysics. He laid the basis of the physics of the process; a theoretical model of a wind-blown bubble first suggested by Pikelner (1968) has not undergone significant changes to this day.

However, modern observations of ring nebulae around WR stars have shown that physics of the star-ISM interaction turned out to be much more complicated than the classical theory assumes. The following processes appear to regulate the interstellar environment of WR stars:

(i) the UV-radiation and wind of the progenitor star at the MS stage;

(ii) ejecta of a shell in the couse of the star's evolution;

(iii) common winds (and SNe) of the parent OB-association;

(iv) stellar motion;

(v) inhomogeneous ISM (small-scale cloudlets and large-scale density gradients).

To summarize modern observations very shortly, I should say that bubbles blown by the strong winds of WR stars, first, are never observed "in pure appearance" and, second, as a matter of fact are not observed at all around the majority of WR stars. On the one hand, deep images of the majority of well-known ring nebulae

around WR stars show evinence of a joint action of radiation, stellar wind and stellar ejecta leading to a multi-layer shell-like structure in the surrounding ISM. On the other hand, only about 30% of WR and Of stars in the distance-complete sample in the Galaxy are associated with ring nebulae; the stellar ejecta and wind-blown bubble types are even more scarce, comprising a fraction of about 10–15% (Lozinskaya, 1982, 1983, 1992; Miller and Chu, 1993; Marston et al., 1994a, b). On the contrary, theory predicts that every WR star should be surrounded by at least two shells: a large "interstellar" shell swept up by the MS progenitor and a small bubble of circumstellar or interstellar gas swept up by the strong wind at the WR stage. Perhaps the lack of ring nebulae around many WR stars is a result of evacuating the surroundig interstellar gas by the wind of progenitor star itself at the MS stage and/or by common winds (and supernovae) of the parent OB-association.

A deep emission-line imaging survey of the (almost complete) WR-star population in the Magellanic Clouds (Dopita et al., 1994) opens an opportunity to clarify different aspects of WR star interaction with the surrounding circumstellar and interstellar gas. Interference filter CCD images have been obtained for all WR stars in the Magellanic Clouds: 115 WR stars in the LMC and 9 WR stars in the SMC were observed in H-alpha and [OIII] 5007A using the 2.3 m telescope at the Siding Spring Observatory ANU.

This survey is the first complete survey of the ionized material around WR stars in the Magellanic Clouds, and is indeed the first complete survey in any galaxy. As a result, the number of ring nebulae known in the MC has been almost doubled, and a number of cases almost certainly identified as stellar ejecta have been revealed.

Here we consider the interstellar environment of WR stars using the new deep search and taking into account the detectability of ejected and swept up shells. Two advantages of the LMC are essential: the completeness of the WR sample and relatively low mean number density of the ISM.

For a limiting emission measure of 10 cm^6 pc, a 5 to $10M_\odot$ ejected shell would fade away at a radius of 4 to 7 pc if the shell's geometrical thickness is (0.1–0.2)$R_\odot$. For an expansion velocity of 50–100 km/s the duration for detectability is only a few times 10^4 yr, which is about 10% of the WR phase lifetime. (All the above parameters are typical of well-studied ejecta in the Galaxy). On the other hand, for the same limiting emission measure and thickness, the minimal radius of a detectable swept-up interstellar shell corresponds to 100–200 pc for an ambient density $n_0 = 0.1$ cm^{-3} and to 5–10 pc for $n_0 = 0.5$ cm^{-3}.

Therefore, in a low-density area we, first, should see ejecta-type nebulae only around about 10% of WR stars even if every star has ejected a shell in the course of evolution and, second, we can try to discriminate ejected and swept-up interstellar shells.

Among 155 WRs in the LMC, Dopita et al. (1994) selected 31 WR stars which appear to be located in regions of a low ambient density of about 0.5 cm^{-3}. Large faint ring nebulae of a typical size from 50 to 300–400 pc are found to be related to 64% of the "selected" WR stars. These big rings most probably display bubbles blown by the progenitor winds at the Main Sequence and/or by common winds of the parent OB associations. The winds of the associations seem to dominate for the

majority of big rings. Indeed, according to the statistics the majority of WR stars which belong to OB associations are related to big shells (100% among "selected" and 86% among all WRs excluding those located in the overcrowded 30 Dor area, see Tables 1 and 11 in Dopita *et al.*, 1994). The percentage of big shells around "isolated" WR stars is less than 50% in both samples.

Small ring nebulae are found to exist around eleven of the "selected" WR stars, all of them but one related to big swept-up shells. Thus the incidence of ring nebulae around WR stars in the LMC is very similar to that in the solar neighborhood. The inner "small rings" might probably display a circumstellar material.

Therefore, the statistical evidence for the LMC does not contradict to the suggestion that all WR stars may eject a stellar shell of a typical mass about $5-10 M_\odot$ at a velocity of about 50 to 100 km/s; the strong stellar wind sweeps up the ejected material. Because of the evacuation of the surrounding gas by the wind of the progenitor star and of the parent OB-association we detect a ring nebula around a WR star provided there is an ejected circumstellar material and as long as its emission measure is detectable.

The distribution of the small WR-rings over spectral types (see Table 3 and Table 4 in Dopita *et al.*, 1994) confirms the available statistics for the Galaxy (though the sample is poor for WN8 and for the "selected" WC stars) in the following aspects:

first, the scarcity of small rings around WNL stars;

second, a low percent of WC stars with small ring nebulae;

and third, a high percent of WN8 stars with small ring nebulae. The only WN8 nebulae in the sample of selected stars is of ejecta type.

The sizes of small ring nebulae related to the "selected" WRs of different spectral types are the following: ring around WNE stars have sizes in the range 3 to 30 pc; two WC-ringes are among the largest (of a size 30–45 pc); and two rings around WN7 and WN8 are among the smallest (smaller than 10 pc). The statistics is poor though consistent with an evolutionary sequence from WNL to WC, with both young and old stars in the LMC belonging to WNE types as suggested by Breysacher (1986).

Another view on the stellar wind action on the ISM is provided by a study of a very rare population of oxygen WR stars (WO). Among the more than 400 WR stars known in the Local Group galaxies, there are only five extreme objects classified as WO: two in the Galaxy (WR 102 and WR 142), BR 93 in the LMC, Sand 1 in the SMC, and a WO star in IC 1613. According to Barlow and Hummer (1982), WO stars can be considered as a separate sequence (after WC) which represents a late stage close to carbon burning in the core of a very massive star. Dopita *et al.* (1990) proposed that WR 102 can possibly be the stripped CO core of a star of M(init) about $60 M_\odot$ with $M(init)$ the inital stellar mass. Although Polcaro *et al.* (1992) questioned the assertion of Dopita *et al.* (1990) that WR 102 completely lacks He in its envelope, the position on the H–R diagram indicates that the star is at the endpoint of its evolution. Since the lifetime of a star with $M(init) = 40-60 M_\odot$ in the nuclear C burning stage is only 0.3–1% of the He burning period (the WR stage), observations of WO stars provide a unique opportunity to study SN environ-
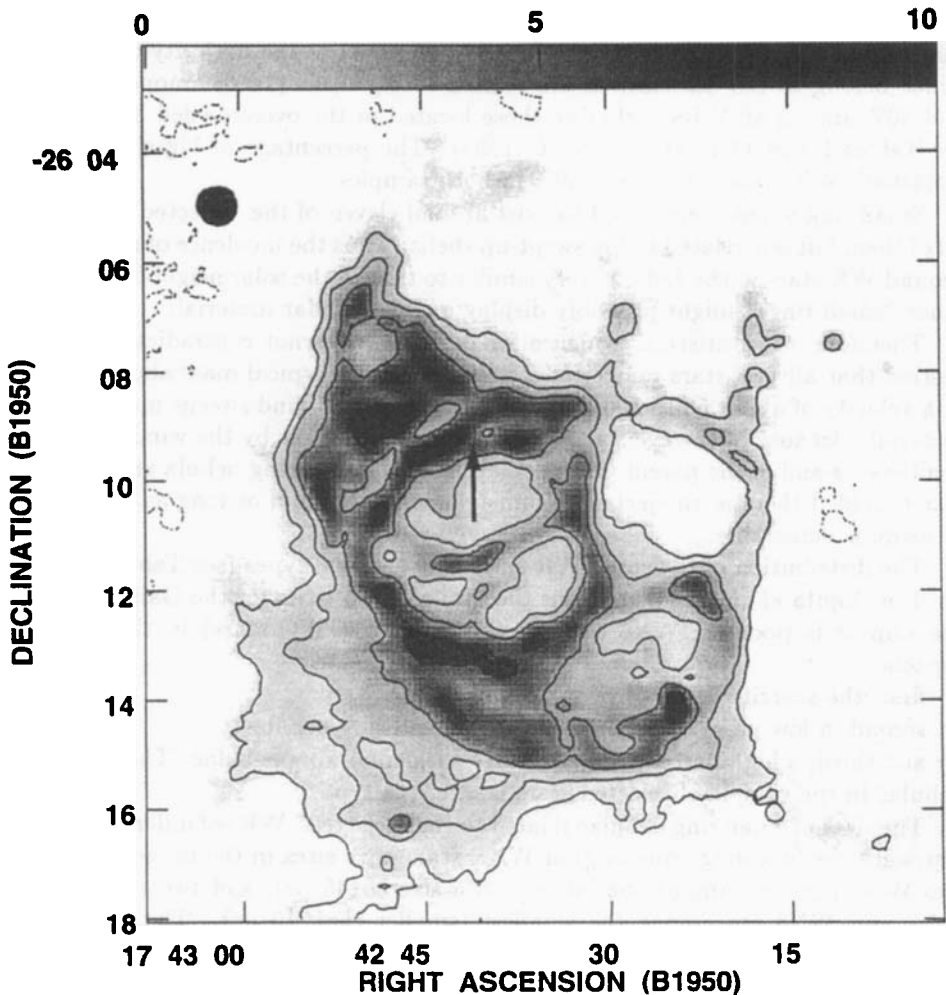
Figure 1 *a*, VLA image of G2.4+1.4 at 1490 MHz from Goss and Lozinskaya (1995) Gray-scale flux range is 0 to 10.0 mJy beam^{-1}; the contour levels are -1 (*dotten line*), 1, 2, 4, and 8 mJy beam^{-1}. The W-R star position is at $\alpha(1950) = 17^h42^m40\overset{s}{.}5$, $\delta(1950) = -26°09'20''$ (shown by the arrow).

ments shortly before the explosion. Because of their short lifetime, the five known WO stars comprise a representative sample. WO stars are characterized by fast superwinds at the terminal velocities 4500–7500 km/s (Barlow and Hummer, 1982; Torres *et al.*, 1986; Dopita *et al.*, 1990; Polcaro *et al.*, 1992) and the ambient gas is influenced by previous regular winds from the WR and main sequence stages. The effective temperatures of WO stars are expected to exceed 10^5 K (Maeder and Meynet, 1989). Observations of WR 102 (Dopita *et al.*, 1990; Melnick and Heydari–Malayeri, 1991) and WR 142 (Polcaro *et al.*, 1991) as well as the presence of strong He II 4686A emission in nebulae around WO stars (Garnett *et al.*, 1991a, b) confirm high stellar temperatures.
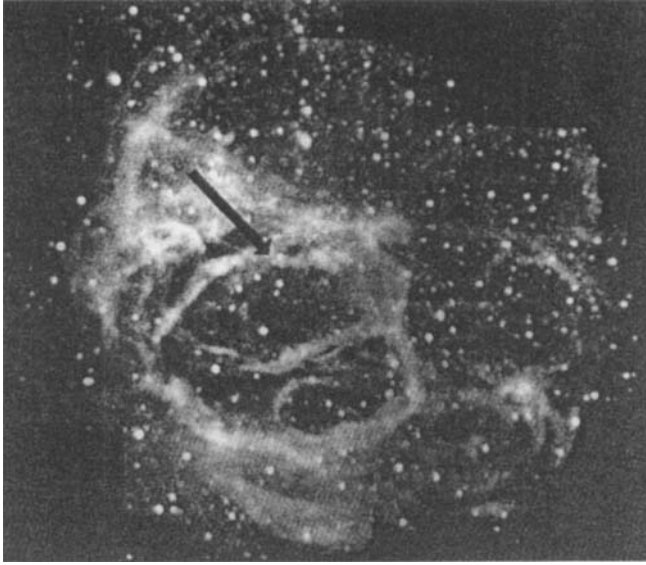
Figure 1   *b*, Deep image of G2.4+1.4 in *H*α line from Dopita *et al.* (1990), with the same scale as in (*a*). The star WR 102 is indicated by the arrow.

Goss and Lozinskaya (1995) presented new VLA and IRAS observations of two H II regions: G2.4+1.4 associated with WR 102 in the Galaxy and the H II region Sandage No. 3 around the WO star in IC 1613.

The ring nebula G2.4+1.4 was suggested to be a SNR since its radio spectrum was thought to be nonthermal even though the WR star was recognized as a source of ionizing radiation and stellar wind (Johnson, 1975, 1976; Treffers and Chu, 1982; Chu, Treffers and Kwitter, 1983). Alternative interpretations as a wind-blown bubble around a WR star, or as a SNR illuminated by a WR star or even as an unusual wind-blown bubble with nonthermal radio spectrum were also considered (see Chu *et al.*, 1983; Green and Downes, 1987, and references therein). None of the models fitted the observational data satisfactorily. Dopita *et al.*, (1990) and Dopita and Lozinskaya (1990) carried out detailed studies of WR 102 and G2.4+1.4. The shell-like nebula was shown to be at least twice as large as previous optical images had suggested. The model proposed was a blister type wind-blown bubble at the edge of a dense cloud. A major outstanding problem for the model was the nonthermal radio spectrum suggested by Johnson (1975). Marston *et al.* (1994b) have recently detected a second larger diffuse H-alpha ring of a diameter of 12' outside the inner brignt ring G2.4+1.4, while a third even more diffuse ring exists outside these two.

Figures 1*a*, *b* show the new 1.49 GHz image of G2.4+1.4 obtained by Goss and Lozinskaya (1995) together with the H-alpha image from Dopita *et al.* (1990). The VLA image shows the filamentary shell extending much farther to the north and west than shown previously by Green and Downes (1987), based on a VLA 6 cm snapshot. In addition, a larger diffuse nebula is seen to the south-east and south of
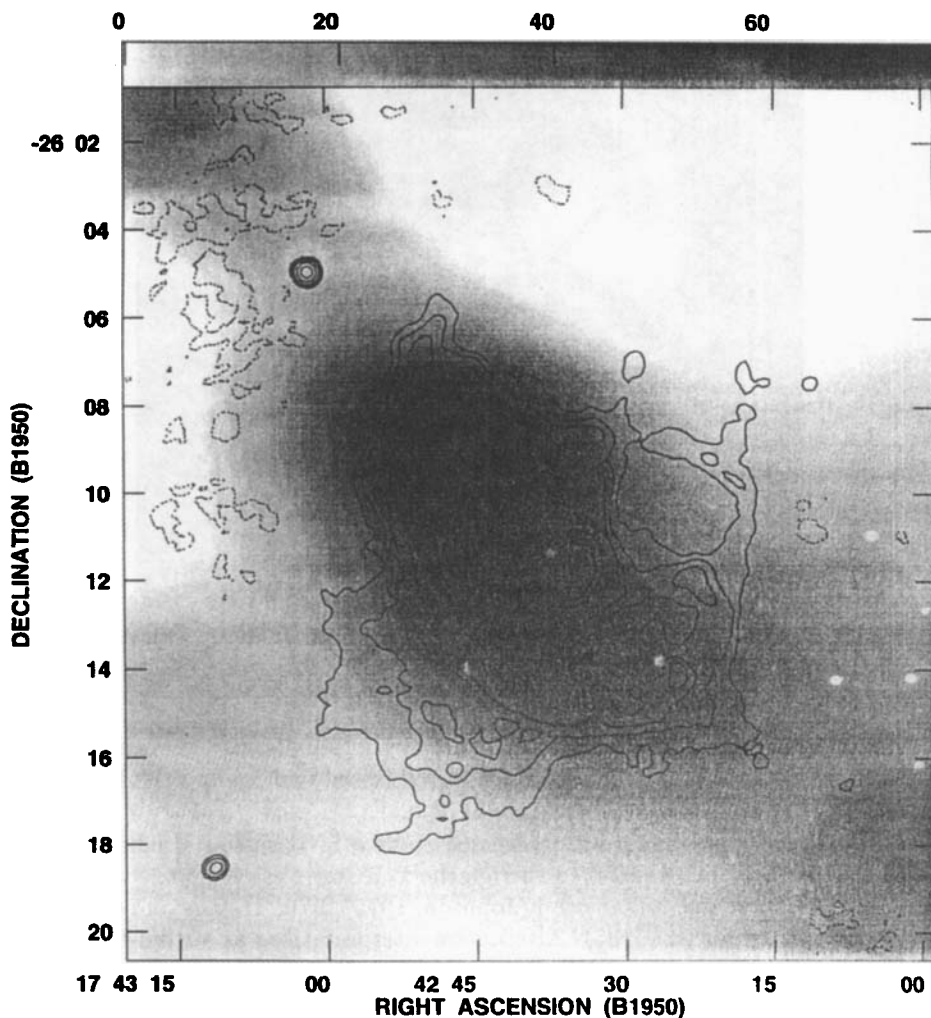
Figure 2 G2.4+1.4: superposition of the 1490 MHz image (contours) and IRAS FRESCO, 100 μm band image (gray-scale range from 0 to 100 mJy sr^{-1}) from Goss and Lozinskaya (1995).

the filamentary shell. A very good correlation of the thin-filament radio morphology with that observed in the H-alpha line is evident.

At 1.49 GHz the total flux density of G2.4+1.4 is 2.4±0.2 Jy; a comparison with observations at 843 MHz (Gray, 1993) implied a spectral index $\alpha = -0.15 \pm 0.20$ (Goss and Lozinskaya, 1995). Therefore, there is no longer any compelling evidence for a nonthermal radio source.

The radio morphology more clearly displays the same general picture as revealed in optical lines: a filamentary shell (a wind-blown bubble of a size 11–10 arc min or 9–10 pc) which lies inside a more diffuse H II region of about 15–16 arc min or

13–14 pc (based on a distance of 3 ± 1 kpc). The parameters of the filamentary shell derived are: $EM = 4.1 \times 10^3$ pc cm^{-2}, $n_e = 60$ cm^{-3}; the excitation parameter $u = 38$ pc cm^{-2} and the mass of ionized gas is about $100 M_\odot$; the mass of the diffuse H II region is about 150–$170 M_\odot$ and $n_e = 5$ cm^{-3}.

In Figure 2, from Goss and Lozinskaya (1995) the 1.49 GHz radio image (contours) is superimposed on the 100 micron IRAS FRESCO images of G2.4+1.4 represented as a grey-scale map. The IRAS source has the same angular size and shape as the brighter portions of the radio source and the optical nebula, indicating that the IR radiation originates from the filamentary shell G2.4+1.4. The nebula G2.4+1.4 has a higher temperature ($T_{\rm dust} = 30.0$–30.5 K) than the surroundings ($T_{\rm dust} = 27$–28 K), similar to that of other WR-ring nebulae (Marston, 1991; Mathis et al., 1992). Assuming that the IRAS flux densities mainly arise from dust emission, Goss and Lozinskaya (1995) estimated the mass of dust in the nebula to be about $M_{\rm dust} = 0.6$–$1.2 M_\odot$ and the total mass to be $M_{\rm gas} = 100$–$200 M_\odot$ in a good agreement with the 1.49 GHz data.

The large-scale IRAS image of the region shown in Figure 3 displays a large shell with WR 102 and its optical, radio and IR nebula G2.4+1.4 located at the brightest north-east edge while the $I(60)/I(100)$ temperature image shows a hot spot around WO 102 (see also Lozinskaya, 1991). The size of the large shell is about 60×30 arc min or about 50×25 pc if located at the same distance as WR 102. In terms of the classical theory of a wind-blown bubble the WO star's mechanical luminosity, $L_w = (0.5$–$2)10^{38}$ ergs s^{-1} (Dopita and Lozinskaya, 1990), appears to be sufficient to produce a shell of that size for an ambient gas density of about 2–4 cm^{-3}. However, the corresponding shell dynamical age of $(1.5$–$2)10^5$ yr appears to be much longer than the WO superwind duration. Thus it seems more reasonable to assume that the large shell is caused by the wind at the previous main sequence stage. The location of the star at the edge rather than at the center of the shell needs an explanation; the motion of the star from the OB association Sgr OB5 is one possibility. Sgr OB5 is located at $l = 357$ to 2 deg, $b = -4.8$ to 1.4 deg at the same distance 3 kpc (Humphreys, 1978). The brightest star of Sgr OB5 is of $Mv = -9.4$, the second brightest after Cyg OB2 which is believed to be the youngest association in the Galaxy. Thus Sgr OB5 looks reasonable as a birthplace for the very massive progenitor of WR 102.

The WO star in the Local Group galaxy IC 1613 was discovered by D'Odorico and Rosa (1982) and by Davidson and Kinman (1982) in the core of the H II region No. 3 in the list of Sandage (1971). The H II region No. 3 is of a size 29×9 arc sec or 100×30 pc; strong He II emission arises from its central part (Garnett et al., 1991a, b). Deep H-alpha images obtained by Hodge et al. (1990), and Hunter et al. (1993) show a complex structure with a bright, elongated, previously known nebula Sandage No. 3 and an extended fainter surrounding emission.

Goss and Lozinskaya (1995) have first discovered a thermal radio source with a similar morphology as a bright portion of the optical nebula. The derived EM is 1.1×10^3 pc cm^{-6} and the rms mean electron density is 3.5 cm^{-3}. The excitation parameter is 100 pc cm^{-2} while the total mass of ionized gas is $2.8 \times 10^4 M_\odot$, both consistent with the suggestion that the WO star is the only source of ionization.
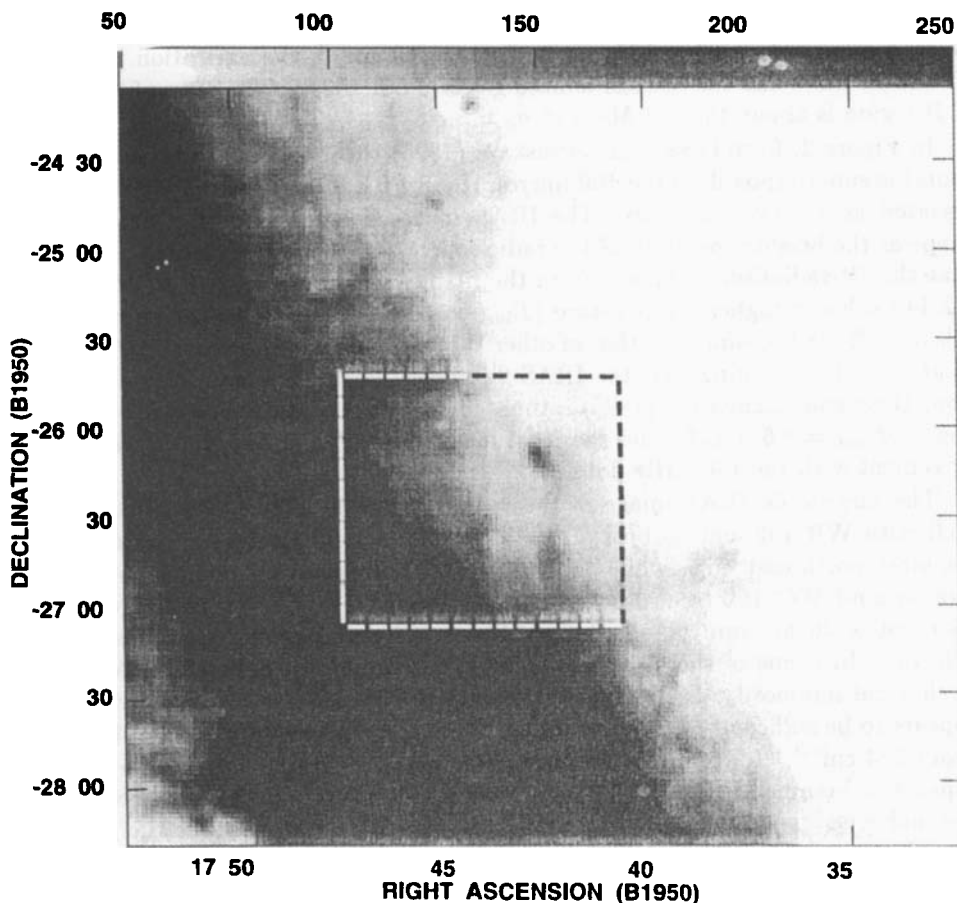
Figure 3   The summed IRAS 60 μm Skyflux image for a 4° × 4° region. *Inside the dashed eine is a large shell-like feature with WR 102 and its optical/radio/IR nebula G2.4+1.4 seen as the brightest spot at the northwestern edge of the large shell* (Goss and Lozinskaya, 1995).

However, we cannot exclude the existence of other sources of ionizing radiation in this H II region.

IRAS FRESCO images of the galaxy IC 1613 show that the WO star and its nebula belong to a giant complex of dust and gas 2–3 kpc in size which includes a region of active star formation with a SNR, and the majority of the giant H II regions in the galaxy, see Figure 9 in Goss, Lozinskaya (1995). The mass of the dust is about $1500 M_\odot$, the total mass is $1.5 \times 10^5 M_\odot$ if the gas-to-dust ratio in IC 1613 is about 100; this appears to be typical of a giant molecular cloud, a site of star formation. The southern component of the IR source encompasses the WO nebula Sandage No. 3.

Therefore, modern studies of the rare population of WO stars as well as our discussion of WR-ring nebulae in the LMC confirm that interstellar environments

at the endpoint of a massive star evolution is affected by the radiation and mass-loss of both the progenitor star and of the parent OB association. A star-formation history of the parent giant molecular cloud may essentially determine the interstellar environment of a WR star.

References

Barlow, M. J. and Humter, D. G. (1982) In *IAU Symp. 99, Wolf–Rayet Stars: Observations, Physics and Evolution*, C. W. H. de Loore and A. J. Willis (eds.), Dordrecht, Reidel, p. 387.
Breysacher, J. (1986) *Astron. Astrophys.* **160**, 185.
Chu, Y.-H., Treffers, R. R., and Kwitter, K. B. (1983) *Ap. J. Suppl.* **53**, 937.
Davidson, K. and Kinman, T. D. (1982) *PASP* **94**, 634.
Dopita, M. and Lozinskaya, T. A. (1990) *Ap. J.* **359**, 419.
Dopita, M., Lozinskaya, T. A., McGregor, P. J., and Rawlings, S. J. (1990) *Ap. J.* **351**, 563.
Dopita, M., Bell, J. F., Chu, Y.-H., Lozinskaya, T. A. (1994) *Ap. J. Suppl.* **93**, 455.
Garnett, D. R., Kennicutt, R. C., Chu, Y.-H., and Skillman, E. D. (1991a) *PASP* **103**, 850.
Garnett, D. R., Kennicutt, R. C., Chu, Y.-H., and Skillman, E. D. (1991b) *Ap. J.* **373**, 458.
Goss, W. M., Lozinskaya, T. A. (1994) *Ap. J.* **439**, 637.
Gray, A. D. (1994) *MNRAS* **270**, 835.
Green, D. A. and Downes, A. J. B. (1987) *MNRAS* **225**, 221.
Hodge, P., Lee, M. G., and Gurwell, M. (1990) *PASP* **102**, 1245.
Hunter, D. A., Hawley, W. N., and Gallagher, J. S. (1993) *Astron J.* **106**, 1797.
Humphreys, R. M. (1978) *Ap. J. Suppl.* **38**, 309.
Johnson, H. M. (1975) *Ap. J.* **198**, 111.
Johnson, H. M. (1976) *Ap. J.* **206**, 243.
Lozinskaya, T. A. (1982) *Astrophys. and Space Sci.* **87**, 313.
Lozinskaya, T. A. (1983) *Pis'ma Astron. Zh.* **9**, 469 (*Sov. Astron. J. Letters* **9**, 247).
Lozinskaya, T. A. (1992) *Supernovae and Stellar Wind in the Interstellar Medium*, AIP, New York, p. 466.
Lozinskaya, T. A. (1991) In *Wolf–Rayet Stars and Interrelations with Other Massive Stars in Galaxiess, IAU Symp. 143*, K. A. van der Hucht and B. Hidayat (eds.), Dordrecht, Kluwer, 365.
Maeder, A. and Meynet, G. (1989) *Astron. Ap.* **210**, 155.
Marston, A. P. (1991) *Ap. J.* **366**, 181.
Marston, A. P., Chu, Y.-H., Garcia–Segura, G. (1994a) *Ap. J. Suppl.* **93**, 229.
Marston, A. P., Yocum, D. R., Garsia–Segura, G., Chu, Y.-H. (1994b) *Ap. J. Suppl.* **95**, 151.
Mathis, J. S., Cassinelli, J. P., van der Hucht, K. A., Prusti, T., Wesselius, P. R., and Willams, P. M. (1992) *Ap. J.* **384**, 197.
Melnick, J. and Heydari–Malayeri, M. (1991) In *WR Stars and Interrelations with Other Massive Stars in Galaxies, IAU Symp. 143*, K. A. van der Hucht and B. Hidayat (eds.), Dordrecht, Kluwer, 409.
Miller, G. J. and Chu, Y.-H. (1993) *Ap. J. Suppl.* **85**, 137.
D'Odorico, S. and Rosa, M. (1982) *Astron. Ap.* **105**, 410.
Pikelner, S. B. (1968) *Astrophys. Lett.* **2**, 97.
Polcaro, V. F., Giovanelli, F., Manchanda, R. K., Norci, L., and Rossi, C. (1991) *Astron. Ap.* **252**, 590.
Polcaro, V. F., Viotti, R., Rossi, C.,and Norci, L. (1992) *Astron. Ap.* **265**, 563.
Sandage, A. R. (1971) *Ap. J.* **166**, 13.
Torres, A. V., Conti, P. S., and Massey, P. (1986) *Ap. J.* **300**, 379.
Treffers, R. R. and Chu, Y.-H. (1982) *Ap. J.* **254**, 132.