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LARGE *IRAS* SHELLS AROUND GALACTIC WOLF-RAYET STARS AND THE O STAR PHASE OF WOLF-RAYET EVOLUTION

A. P. MARSTON

Department of Physics and Astronomy, Drake University, Des Moines, Iowa 50311
Electronic mail: tm9991r@acad.drake.edu

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ABSTRACT

We present *IRAS* Skyflux images of the environments of galactic Wolf-Rayet stars. These form a complete sample of all galactic Wolf-Rayet stars of the van der Hucht *et al.* (1981) catalog observed by *IRAS*, a total of 156 stellar environments. The intent of this survey is to obtain information on the large bubbles expected from the early O star phase of Wolf-Rayet stars. A total of 49 probable or suspected shells of $>20'$ in diameter have been observed in our data, with a detection rate of 60% for large *IRAS* shells around Wolf-Rayet stars at galactic latitudes $>2°$. Fourteen of the *IRAS* shells are associated with previously observed, slowly expanding H I bubbles. Most shells are unlikely to be due to line-of-sight coincidence, although two shells may be associated with foreground or background supernova remnants. In considering the origin of the shells we indicate that most are unlikely to have formed from the explosion of a binary companion to a Wolf-Rayet star and that few, if any, are likely to be associated with ejecta produced in a Roche Lobe overflow. The sizes of the shells, together with their known or estimated expansion velocities are consistent with the estimates of the period of the O star progenitor phase calculated in evolutionary models of single WR stars. © *1996 American Astronomical Society.*

1. INTRODUCTION

In the past few years a number of Wolf-Rayet (WR) stars have been observed as having multiple, concentric rings of material around them (Dopita *et al.* 1994; Marston 1995a). In Marston (1995a) it was shown how such multiple shells are likely to be indicative of several phases of evolution of WR stars, as they evolve from their O star progenitor state. A three phase evolution, starting with an O star proceeding through a high-mass-loss phase (e.g., Luminous Blue Variable) and continuing to the WR star phase, is consistent with the optical and infrared data presented on nebulae around WR stars (Marston 1995a; Marston 1995b). The most recently ejected/swept-up material is observed closest to the stars and can frequently be observed in narrow-band imaging (Miller & Chu 1993; Marston *et al.* 1994a; Marston *et al.* 1994b). These shells of material are associated with a heavy mass-loss phase followed by a strong stellar wind phase which occurs in the WR phase of the star. Further out from a WR star resides a shell of swept up interstellar medium possibly associated with the stellar wind of the star during its O star progenitor phase. Although occasionally observed optically around WR stars (approximately 8% of all WR stars show such extended shells optically, Marston 1996), such shells are expected to be of predominantly cool material and may be more readily observed at far-infrared wavelengths or using radio/sub-mm emission lines of atomic or molecular gas. As an example, the WR star WR136 (numbering from van der Hucht *et al.* 1981) is surrounded by multiple shells of material, with a large outer ring seen using *IRAS* Skyflux (Nichols-Bohlin & Fesen 1993) and *IRAS* high-resolution (HIRES) data (Marston, 1995b). A number of WR stars have been shown to be inside of large H I bubbles of similar dimensions to that around WR136 (Arnal 1992; Cappa de Nicolau & Niemela 1984; also see Marston 1995b, and references therein).

It was shown in Marston (1995b) how the sizes of the concentric shells associated with the O star phase, ejecta phase and WR wind phase, plus information on their expansion velocities could provide time scales for each part of a three phase evolution for WR136. While estimates of total mass loss from the central WR star in the final phases could be estimated based on *IRAS* fluxes of the ejecta shells. The mass of swept-up material in extended *IRAS* shell may also be estimated using *IRAS* fluxes, which Marston (1995b) associates with a bubble created by the O star progenitor of WR136.

As an alternative, Nichols & Fesen (1994) have suggested that large *IRAS* shells seen around WR136 and WR40 arise during the evolution of binary WR stars. They suggest that the large *IRAS* shells in these cases may arise from the supernova explosion of a binary companion to a WR star, or from ejecta during a Roche Lobe overflow from the WR star progenitor onto a compact companion.

In order to obtain more information on the evolution of WR stars, we have embarked on an *IRAS* survey of galactic WR stars. This has involved a survey of *IRAS* Skyflux data associated with the environments of WR stars (providing information on large shells), plus a complementary survey program of HIRES *IRAS* data (Aumann *et al.* 1990), for more

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detailed analysis of smaller shells and mass-loss associated with stellar ejecta.

In this paper we present the findings of our Skyflux survey of the regions around 156 galactic WR stars using *IRAS* Skyflux data at 12, 25, 60, and 100 μm wavelengths. The intent of this survey is to find large ($>20'$) shells associated with galactic WR stars. In the following sections we describe the data used and the results of the analysis of the Skyflux fields. We discuss the formation of the large shells via both WR binary and single star evolutionary modes. From the sizes of the *IRAS* shells observed, their statistical frequency and the (limited) knowledge of their dynamics we determine the most likely origin of large *IRAS* shells and what they can tell us about the evolution of the WR stars they surround.

2. DATA USED

We have surveyed the fields of 156 galactic WR stars of the catalogue of van der Hucht *et al.* (1981) using *IRAS* Skyflux data, which consists of images made of the sky at wavebands centered on 12, 25, 60, and 100 μm. The two stars WR72 and WR99 in the catalog of van der Hucht *et al.* (1981) were omitted as they are not now classified as WR stars (van der Hucht *et al.* 1988). Each region investigated was of 6 degrees square centered on one of the 156 galactic WR stars. Our survey therefore provides coverage of approximately 80% of all known galactic WR stars at mid- and far-infrared wavelengths (van der Hucht 1996).

Evidence for large shells ($>20'$) was searched for around each of the stars in the survey. Structures of complete or partial shells apparently centered close to or on the position of the WR star were deemed associated with the star. In certain cases, the association was corroborated by previously obtained optical images or H I data. Size estimates were made via a fitted ellipse to the observed shell structure.

In certain cases, estimates of the far-infrared fluxes associated with the large shells were possible from the data. The flux interior to an ellipse around each shell was obtained and a local background external to the ellipse removed to obtain these fluxes.

3. RESULTS

A total of 49 probable shells associated with WR stars were found with diameters greater than $20'$ in the *IRAS* Skyflux data (see Table 1). Of these, 2 were previously noted by Nichols-Bohlin & Fesen (1990, 1993) and one by Dubner *et al.* (1990). This provides an overall detection rate of 31%. Images of each of the associated *IRAS* nebulae are provided in Fig. 1[45]. Fourteen of the observed *IRAS* shells correlate with previously observed H I cavities around WR stars, and are indicated in Table 1. In each of these case, the structure of the faint *IRAS* rings mimics that of the H I holes. H I velocity information confirms the fact that the shells are expanding about the central WR stars. The H I structure around WR125 (Arnal & Mirabel 1991) is not obvious in the Skyflux data, although an extended source centered on the star is seen. This extended structure is likely to be associated with dust-formation in the wind of the star (Williams *et al.* 1992). A nearby pulsar, at the same distance as WR125 has prompted Arnal & Mirabel (1991) to associate the extended H I structures with a supernova remnant which extends around WR125, possibly originating from a high-mass binary companion.

Using the distance data of Conti & Vacca (1990), physical size estimates of the large *IRAS* shells can be obtained, based on their average diameters. These show a range in diameter from 10 to 338 pc (see Table 1). In the case of some nearby WR stars, the observed shell may be associated with a WR wind-blown bubble (W) or ejecta (E) phase. This is certainly the case for the nebula around WR11. The largest shells, around WR33 and WR73, may well be associated with supernova remnants, as these are in the same directions as pulsars PSR 1056−57 and PSR 1609−47, respectively (although at significantly different distances). In considering the positions of 330 pulsars listed in Manchester & Taylor (1981), no other pulsars appear interior to the observed *IRAS* shells.

The number of large shells observed in the *IRAS* Skyflux data is affected by galactic latitude. Figure 2 shows how the detection rate for the observed shells changes with galactic latitude. At the higher latitudes, the detection rate increases quite steeply and 2/3 of all WR stars above a galactic latitude of 2° are observed to have shells larger than $20'$. This suggests that the main cause of non-detection is the confusion of *IRAS* shell sources in the galactic plane. Also, large shells in the plane of the galaxy are more likely to be disrupted through interaction with other wind-blown or supernova remnant shells. Small shells are unlikely to be observed in regions high above the plane of the galaxy, since the low densities of the interstellar medium lead to small shell masses and *IRAS* intensities that are too low for the large *IRAS* shells to be detected. A weak trend of increasing shell size with galactic height can be observed in Fig. 3.

IRAS fluxes were obtained for 10 shells while further *IRAS* flux data was obtained for the extended shell around WR136 from Marston (1995b). The *IRAS* fluxes observed from the shells are listed in Table 2. Typically, the accuracy of the fluxes measured are, at best, within 20%. This is mainly due to the varying background in the large areas over which the shells are observed. In the 14 cases of H I cavities observed around WR stars, the swept-up H I masses (adjusted to the distances quoted by Conti & Vacca 1990) are presented in Table 3, along with derived gas masses from *IRAS* data (based on the model of Marston & Dickens 1988). It should be noted that total gas mass estimates based on *IRAS* data are notoriously inaccurate (see Mathis *et al.* 1992) and with the inaccuracy of the *IRAS* flux measurements the *IRAS* gas mass estimates are probably only slightly better in accuracy than an order of magnitude. In the two cases where H I measurements coincide with *IRAS* measurements, the *IRAS* measurements suggest gas masses that are factors of 1.1 and 3.6 higher than the H I gas masses respectively. However, the total gas mass in *IRAS* shells may well be higher than the H I masses as molecular material might also be expected to exist in the swept-up shells.

If we assume the shells are formed from swept-up interstellar medium, then using the shell sizes from Table 1 together with the estimated gas mass enables estimates of the

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TABLE 1. Properties of the large *IRAS* shells observed around WR stars.

WR[2]	Type	Dist.[1] (pc)	Diam. (′)	Diam. (pc)	b[2] (°)	z[1] (pc)	Comments
2	WN2	5400	116	183	−2.41	−227.7	
3	WN3+abs	8600	60	151	−4.14	−619.9	H I shell
4	WC5	3900	120	136	−2.98	−203.0	H I shell
5	WC6	2500	81	59	−2.15	−93.8	H I shell
6	WN5	1000	171	50	−10.08	−175.1	Shell exterior to ejecta nebula S308
7	WN4	3900	35	39	−0.13	−9.1	Around NGC2359
8	WC6/WC4	3300	81	78	−3.79	−217.7	
11	WC8+O9I	300	75	6.5	−7.69	−40.1	E shell seen optically (Marston *et al.* 1994b)
12	WN7	6300	60	111	−1.97	−216.2	
14	WC7	1800	30	16	−1.64	−51.3	Possible ejecta shell
15	WC6	1800	135	71	−1.08	−34.0	
17	WC5	3700	38	41	−3.69	−237.7	H I shell
21	WN4+O4-6	2700	110	88	−0.90	−42.4	
23	WC6	4300	30	38	−0.03	−2.5	Seen optically (Marston *et al.* 1994a)
24	WN7+abs	2800	65	53	−1.08	−52.1	
30	WC6+O6-8	5700	26	43	−2.61	−260.2	Seen optically (Marston 1995a)
31	WN4+O8V	4300	34	43	0.02	1.3	
33	WC5	9200	120	323	1.9	305.0	
40	WN8	2200	180	115	−4.83	−185.4	Surrounds the ring nebula RCW58
48	WC6+O9.5I	700	133	27	−2.49	−19.1	H I shell
52	WC4	2100	1780	105	4.55	166.6	H I shell
54	WN4	6100	150	278	−2.5	−266.1	H I shell
57	WC7	4000	70	80	−5.03	−350.9	H I shell
58	WN4/WCE	4700	180	248	−3.49	−285.6	
61	WN6	13100	60	229	−3.91	−894.8	
66	WN8	4500	65	85	−1.83	−144.0	
68	WC7	3000	28	25	−1.88	−98.6	
69	WC9	2900	60	51	−4.82	−243.5	
70	WC9+B0I	1300	170	65	−1.81	−41.2	
73	WC9	1900	110	338	3.38	619.7	
77	WC8 (+abs)	1100	32	10	−1.09	−189.1	Possible ejecta shell
82	WN8	4700	110	152	−2.32	−190.0	
85	WN6	3700	27	29	−0.61	−39.8	Seen optically (Marston 1995a)
86	WC7+abs	1900	35	19	1.85	61.3	
87/9	WN7/WN7	1300	34	13	−0.77	−17.4	Seen optically (Marston 1995a)
90	WC7	1300	100	38	−4.76	−108.0	H I shell
101	WN7-8	6900	80	161	−1.43	−172.6	
110	WN6	1800	30	16	0.39	12.0	Possible ejecta shell
123	WN8	6500	24	46	−4.75	−538.3	H I shell
124	WN8	3500	120	123	3.31	202.5	
132	WC6	7100	49	101	1.1	136.3	H I shell
133	WN4.5+O9.5Ib	1200	100	35	2.7	43.3	
136	WN6	1500	91	40	2.43	63.7	Surrounds the ring nebula NGC6888
139	WN5+O6	2400	142	100	1.43	60.0	
140	WC7+O4-5	800	110	26	4.18	58.4	H I shell
148	WN7	5200	36	54	6.47	585.7	H I shell
152	WN3	6200	21	38	−0.89	−95.6	
157	WN4.5 (+B1II)	2300	27	18	−0.24	−9.4	
158	WN7	3900	135	154	0.1	6.8	

Notes to TABLE 1

[1]from Conti & Vacca (1990).
[2]from van der Hucht *et al.* (1981).

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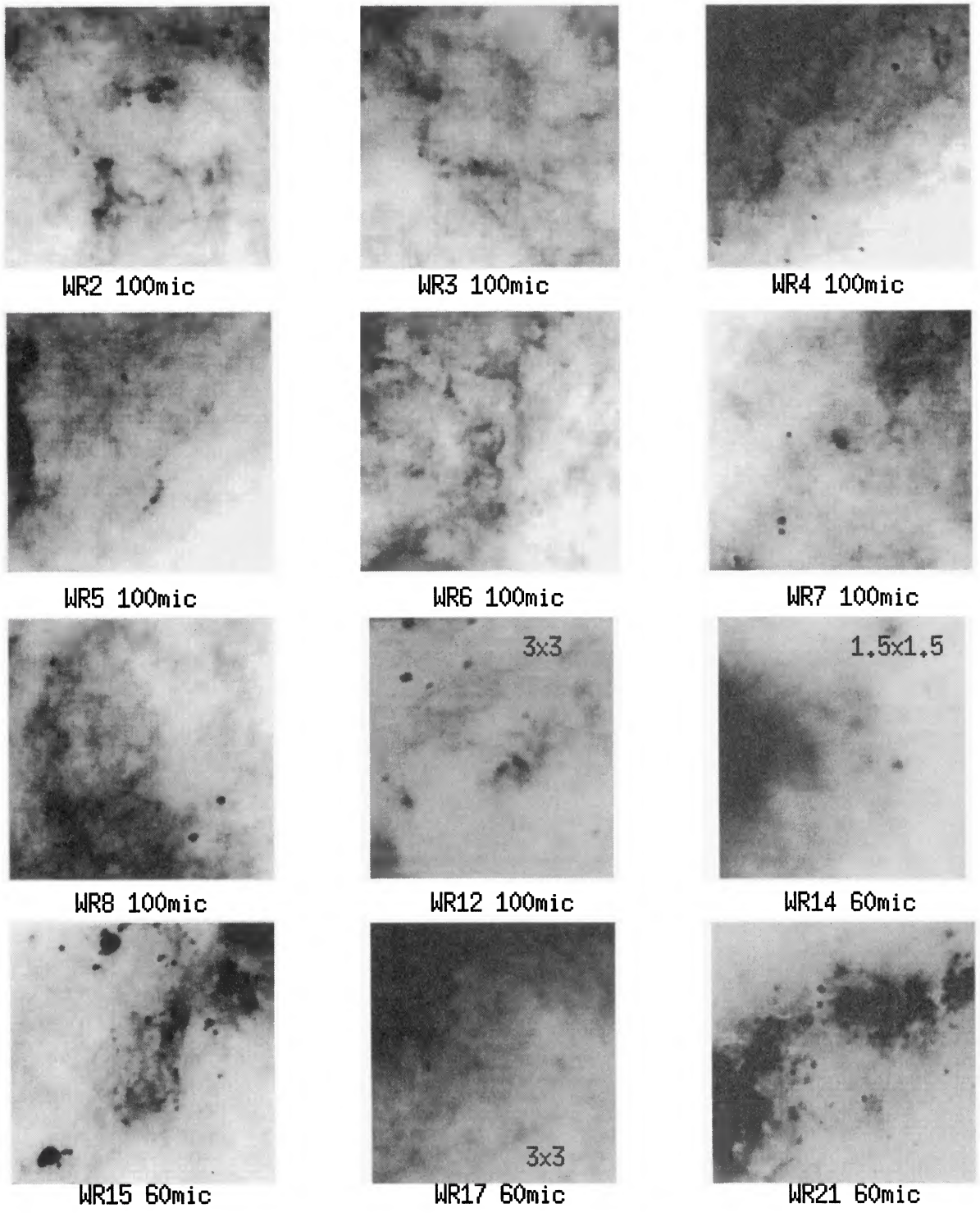


FIG. 1. The large *IRAS* shells observed in the *IRAS* Skyflux data at 60 and 100 μm (the ejecta shell around WR11 is not shown). All fields are 6° square, except where indicated on the image. In all cases the WR star is at the center of the image.

original particle density local to the WR stars to be made. These results are also presented in Table 3.

An inverse relation is noted between shell size and the calculated local density of the interstellar medium (Fig. 4). Shells with diameters of 100 pc or more are associated with low-density surroundings. This is in part due to penetration of such shells out of the densest parts of the galactic disk. Overall, the shell diameters are expected to also be functions of the wind luminosity and the age of the central WR star.

Overall, the detection rates for shells surrounding the WR subtype WN and WC stars are 32% and 31%, respectively (for rings larger than 20′), while 2 of 6 WN/WC type stars

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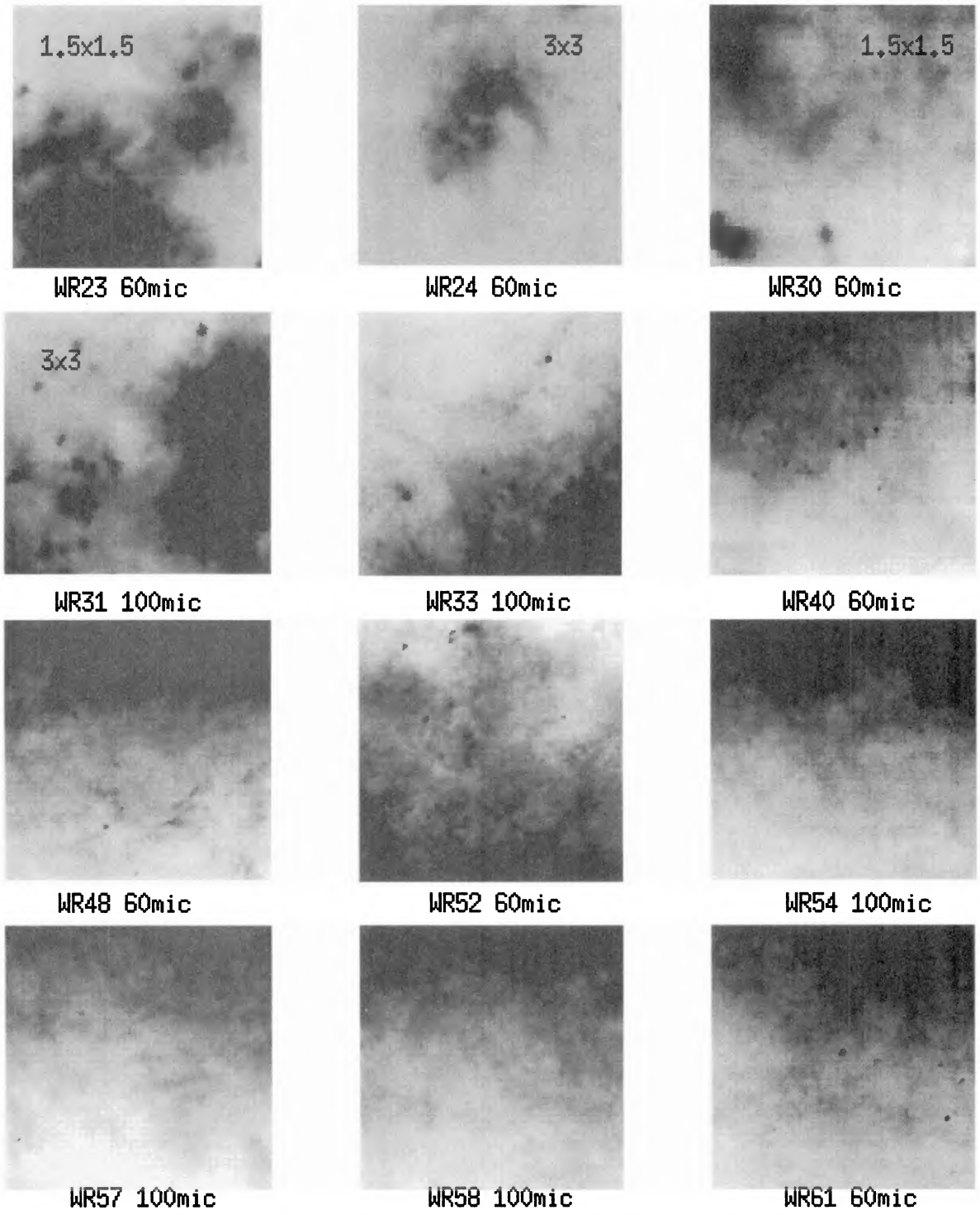


FIG. 1. (continued)

showed such shells, suggesting no bias towards large shell formation around a particular subtype.

4. DISCUSSION

The origin of large *IRAS* shells apparently associated with WR stars has been a subject of some debate. Line-of-sight coincidence appears unlikely given the connection with H I features with similar kinematical distances as the central WR stars (e.g., Arnal 1992). The central location of most stars in the *IRAS* shells also argues strongly against many coincidences.

In Nichols & Fesen (1994), two main alternatives were put forward for explaining the extended shells around WR6, WR40, and WR136 (each of which has a bright optical ring nebula interior to a large *IRAS* shell). Their first suggestion is that large *IRAS* shells are supernova remnants associated with the explosions of binary companions to the WR star.

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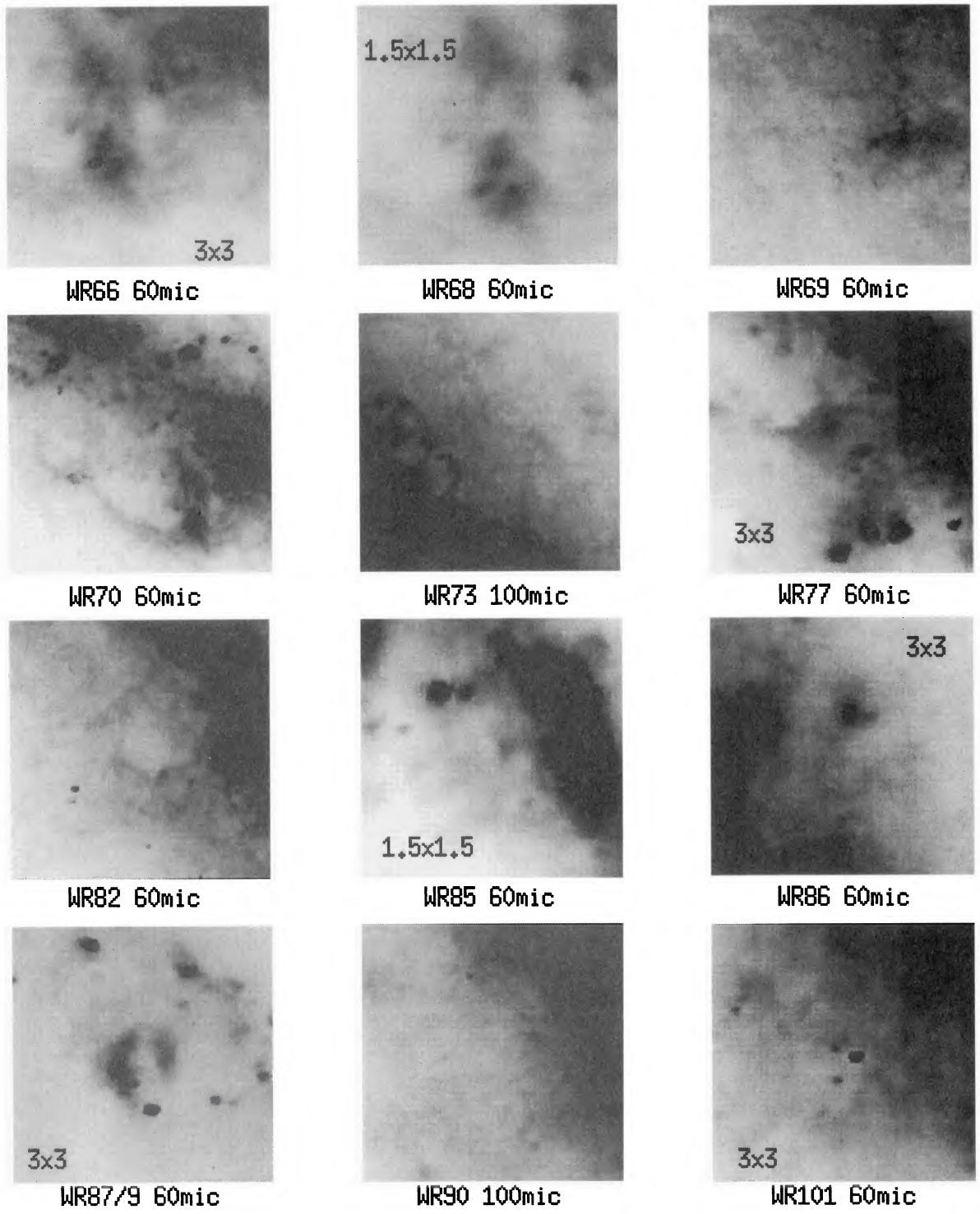


FIG. 1. (continued)

Alternatively, Nichols & Fesen (1994) suggest that material ejected during a Roche Lobe overflow (RLOF) from a WR progenitor onto a compact companion forms the large shells. We now consider these two alternatives as well as the origin of large *IRAS* shells as interstellar matter swept-up during the O star progenitor phase of WR stars.

4.1 Supernova Origin

In this alternative, the extended shells are created from an exploding primary companion at or just before the point where the WR star first becomes a WR star. Nichols-Bohlin & Fesen (1993) suggested that the large (1.7°×1.5°) shell surrounding WR136 is associated with a supernova explosion in the neighborhood of the WR star. This conclusion was based in part on the low Hα/[S II] emission-line ratio seen in optically observed filaments apparently associated with the shell. However, the physical connection of these filaments to the *IRAS* shell is not clear. They may well be associated with supernova material in a super-association, either foreground or background to the *IRAS* shell, perhaps

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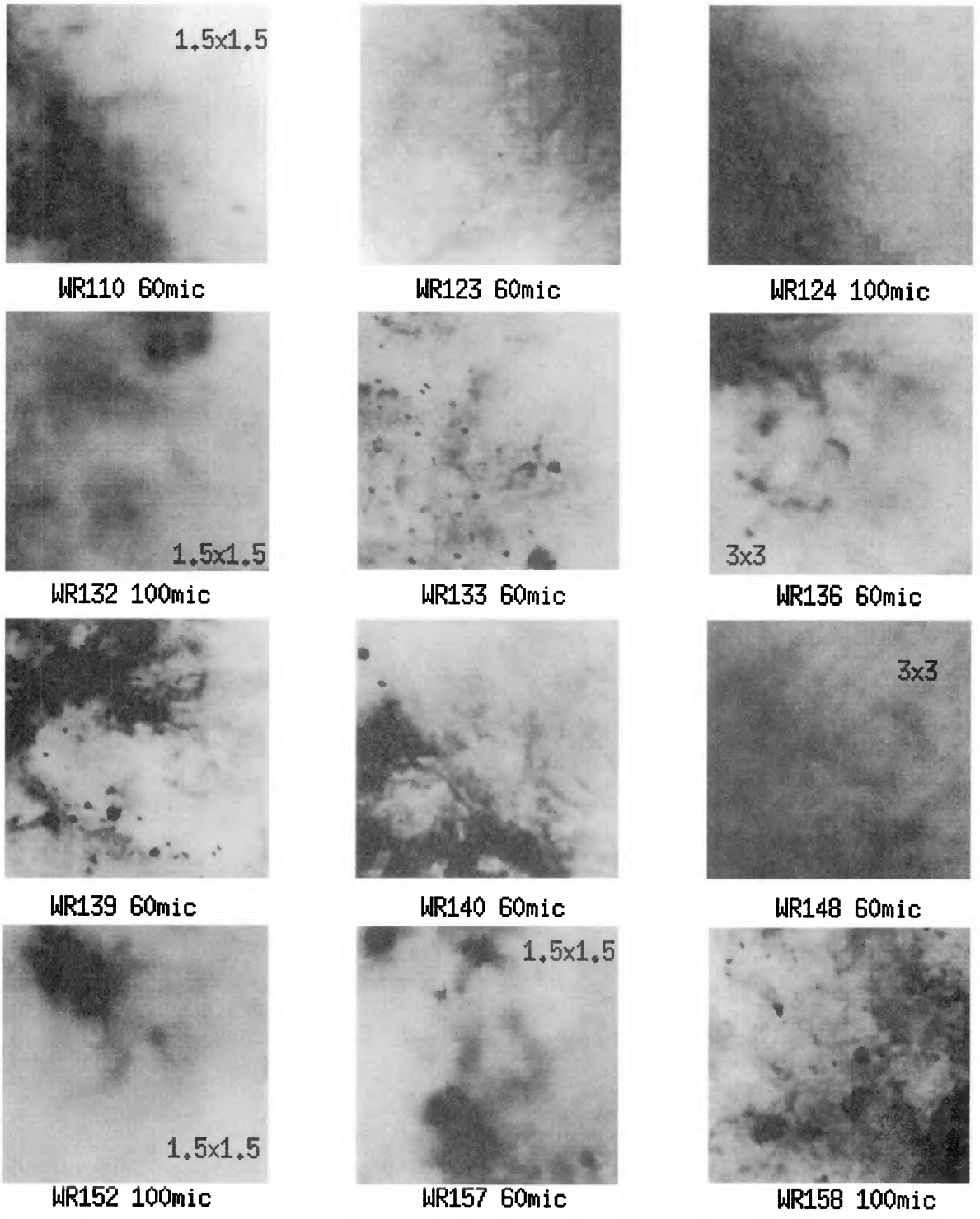


FIG. 1. (continued)

associated with high-velocity UV absorption lines observed in the region (St-Louis & Smith 1991). The high-velocity features appear to extend beyond the large *IRAS* shell and it is unlikely that there is a direct connection between the *IRAS* shell and these high-velocity absorption features.

For the shells around WR6 and WR40 Nichols & Fesen (1994) suggest that the large *IRAS* shells may be associated with high-velocity absorption features observed in the UV leading to the possibility that the large *IRAS* shells are either supernova remnants with ages of 10^5 years, or a similar aged nebula created during a RLOF (see Sec. *4.2*). WR6 and WR40 are 2 of 35 stars with *IUE* observations analysed by Nichols & Fesen (1994). Of these 35 WR stars 43% observed as having high-velocity absorption lines are observed by us to have extended *IRAS* shells, while 50% of those having no associated high-velocity absorption lines also have *IRAS* shells. The *IRAS* shell around WR148 is also noted in H I with an expansion velocity of around 6 km s^{-1} (Dubner *et al.* 1990). High-velocity absorption lines are also noted in the spectrum of this star. All this leads us to conclude that

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there appears to be little correlation between the existence of high-velocity absorption line features and that of a large *IRAS* shell. Indeed, all 14 of the H I observed large *IRAS* shells have expansion velocities of 20 km s^{-1} or lower, which are far smaller than the velocities of the absorbing materials observed in the WR spectra.

We conclude that it is unlikely that supernova remnants are the main origin of large *IRAS* shells around WR stars. Indeed, we further note that none of the *IRAS* shells surround both a pulsar and a WR star.

4.2 Mass Ejection due to Roche Lobe Overflow

In this mechanism, a WR star and an OB star exist in a binary. The supernova explosion of the WR star creates a compact companion, which will remain bound if the star system becomes a "runaway." This scenario has the advantage of enabling WR stars to move out of the galactic disk to large distances (>100 pc) above the galactic plane while the O star ages. The O star then evolves towards being a WR star over a period of several million years. As it expands, following the depletion of H in its core, material can flow (RLOF) onto the compact companion at a rate exceeding the Eddington limit. This leads to a mass ejection which Nichols & Fesen (1994) suggest produces the large *IRAS* shells. This ejection leads to shells expanding at high velocities, as is possibly indicated by high-velocity UV absorption lines. The ages of such shells should be approximately 10^5 years.

In Sec *4.1* it was indicated that high-velocity UV absorption lines have no obvious connections to the existence of large *IRAS* shells around WR stars. Also, all shells so far observed using H I measurements exhibit expansion velocities of a few to 20 km s^{-1} (see Marston 1995b, and references therein). The expansion ages of these large shells are therefore of a few million years (see Table 3). This is a magnitude too large for the proposed RLOF mechanism.

The RLOF mechanism nicely explains the existence of runaway WR stars above the galactic plane, however, 11 out of 14 H I observed, large *IRAS* shells noted in this paper, have distances away from the galactic plane of more than 100 pc and may be considered potential runaway stars. None of them show the fast H I expansion velocities.

Although some WR stars are suspected of having compact companions, the numbers are likely to be small. Yungelson & Tutukov (1991) predict that up to 10% of WR stars may have close compact companions, and Vanbeveren (1988) indicates that the number of WR stars with compact companions is likely to be less than 5%. Vanbeveren (1994) also indicates that the likelihood of a bound system after an initial supernova is low due to the large kick velocities involved. But more than 30% of our WR sample show large *IRAS* rings. It appears unlikely that as many as one third of the galactic WR population, that are observed as having large *IRAS* shells, would have the compact companions necessary for the RLOF picture to be the primary mechanism for large *IRAS* shell creation. Further, six stars noted as being in WR+OB binaries also have large *IRAS* shells. It appears certain that no supernova or RLOF phase can have caused the shells associated with these objects.

We conclude that it is unlikely that many (if any) of the large *IRAS* shells are created during a RLOF onto a compact companion to a WR star.

4.3 Wind-blown Bubbles

Nichols & Fesen (1994) suggested that the large *IRAS* shell around WR40, which is well out of the galactic plane, was inconsistent with the fact that similar structures are not to be seen around stars in more dense environments. Our survey indicates that such shells do exist for objects in the galactic plane but are less often observed as such, due to confusion. A distinct increase in the detection rate of observed large shells is seen at high galactic latitudes (see Fig. 2). Also, in Fig. 3 we showed that the extended *IRAS* shells are distinctly smaller at small galactic heights, making them less likely to be observed by *IRAS* as highly extended objects. Marston (1996) has also shown that the detection of optical ring nebulae appears to be independent of galactic latitude, suggesting that the existence of an optically observed ring nebula, usually of an ejecta or wind-blown type, depends on the evolution of the WR star (particularly in its heavy mass-loss, ejecta phase) rather than on its environment.

In Marston (1995a) it was illustrated how multiple optical ring nebulae around WR stars are consistent with a three stage WR evolution from an O star, through a heavy mass-loss phase to becoming a WR star. Marston (1995b) also illustrated that the nebulae associated with WR136 are consistent with this picture. In this case the large *IRAS* shell associated with WR136 is consistent with a wind-blown O star progenitor shell with an age of around 2 million years, a value typical of the total age of the more massive WR stars (Maeder & Meynet 1994). The inner, optically observed ring nebula (NGC 6888) is then interpreted as being associated with an ejecta shell being penetrated by a wind from WR136.

If we make similar assumptions to Marston (1995a), we are able to obtain estimates of the shell ages and therefore the lifetimes, t_{WR}, of the associated WR stars from the radius, r, and the velocity of expansion of the large *IRAS* shell, v_{exp},

$$t(\mathrm{yrs}) = \frac{10^6 r(\mathrm{pc})}{v_{exp}(\mathrm{km\ s^{-1}})}. \quad (1)$$

Only a few of our objects have known expansion velocities (see Table 3). Taking an average expansion velocity of 10 km s^{-1} for the rest of our sample indicates timescales of 0.65 to 16 million years. However, the upper limit is imposed by two observations that may be confused with supernova remnants associated with pulsars in the same line of sight (shells around WR33 and WR73). Removing these leaves an upper limit of 14 million years. It is also possible that some of the smaller shells observed are actually associated with the ejecta phase of the star (we will deal with these in our *IRAS* HIRES survey). Within the errors associated with our calculation (factors of 2), the lifetime of these stars in an O star phase is consistent with estimates from models of single massive star evolution (Maeder & Meynet 1994). A distribution of the ages associated with the large *IRAS* shells

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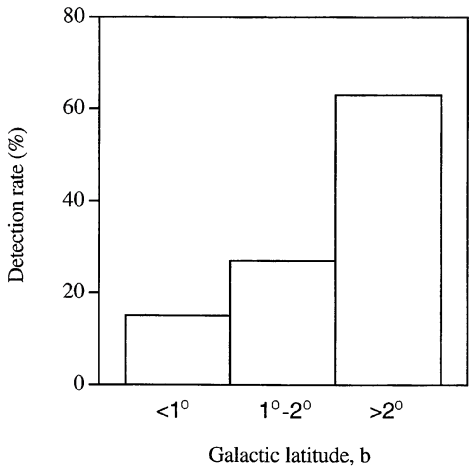


FIG. 2. The variation of large *IRAS* shell detection rate with galactic latitude.

is presented in Fig. 5. Most stars have ages in the range of 1 to 5 million years.

In Fig. 4 it was illustrated that larger shells were generally produced in the less dense environments at 100 pc and more away from the galactic plane. Figure 6 illustrates that the observed *IRAS* shell time scales tend to increase with galactic height (z). This would suggest that less massive WR progenitor stars, with longer O star phases, are being observed at greater galactic height and more massive WR progenitors are observed in the galactic plane, in regions of higher gas density. Another possibility is that the WR stars formed at higher galactic latitudes have lower abundances and a longer O star progenitor phase (Maeder & Meynet 1994). However, these results must be treated with some caution. As noted earlier, the detection of large *IRAS* shells is likely to be biased. At large z, the low density of the interstellar medium would make small *IRAS* shells difficult to distinguish above the background, while confusion in the galactic plane reduces the number of large *IRAS* shells observed at small z. The result of this being a lack of objects of smaller ages at large z and a lack of objects of larger ages at small z.

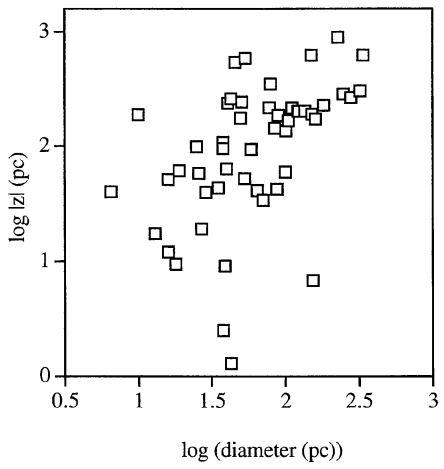


FIG. 3. Comparison of the large *IRAS* shell diameters with galactic height, z.

TABLE 2. *IRAS* fluxes associated with 10 of the sample large rings.

WR	12 μm (Jy)	25 μm (Jy)	60 μm (Jy)	100 μm (Jy)
2	900	840	2850	3915
3	250	280	820	4320
7	15	40	490	1010
15	1520	1960	14040	44950
30	15	25	255	495
33	330	350	3125	12980
48	370	535	3720	9940
87/9	250	3245	18970	23070
133	1780	1170	12800	32000
157	120	205	1840	3790

Notes to TABLE 2

Typical errors on observed fluxes are 20%. For WR2, numerous 12 and 25 μm point sources are in the field and the values quoted here are tentative.

A three phase evolution model does not explain the high-velocity UV absorption line features observed in the UV spectra of some WR and nearby stars. Such absorption features do not appear to be directly related to the existence of extended *IRAS* shells, but what are they associated with? Goudis *et al.* (1988) showed the existence of optical emission-line, metal-rich, high-velocity bullets of material in

TABLE 3. Gas masses in the large shells and derived average densities of the original interstellar medium swept-up into the shells, made from *IRAS* and/or H I data

WR	Mass $M_\odot$	v_{exp} (km s^{-1})	Source	Density particles cm^{-3}
2	9000		1	0.12
3	8400	10	2	0.2
5	2400	8	2	0.8
7	2200		1	2.3
15	41300		1	7.2
17	2500	8	3	3.1
30	2150		1	1.7
33	90000		1	0.22
48	1050		1	3.3
	980	9	4	3.1
52	14000	16	6	0.8
54	15000	12	6	0.05
57	32000	9	6	3.9
61	37000	20	6	0.3
87/9	2580		1	74
90	3620	10	5	5.6
123	7560	8	2	6.6
133	9000		1	13
136	8300		8	8.1
140	710	13	2	3.4
148	5700		1	2.3
	1600	6	7	0.6
157	2900		1	13

Notes to TABLE 3

Sources:1=from *IRAS* data presented in this paper. 2=from Arnal (1992). 3=from Cappa de Nicolau *et al.* (1986). 4=from Cappa de Nicolau & Niemela (1984). 5=from Cappa de Nicolau *et al.* (1988). 6=from Niemela & Cappa de Nicolau (1991). 7=from Dubner *et al.* (1990). 8=from Marston (1995b). H I masses are adjusted to the object distances given by Conti & Vacca (1990). Not included are the data for the H I shells around WR125 (no *IRAS* shell) and WR4 and WR132 (no good estimate of shell mass available).

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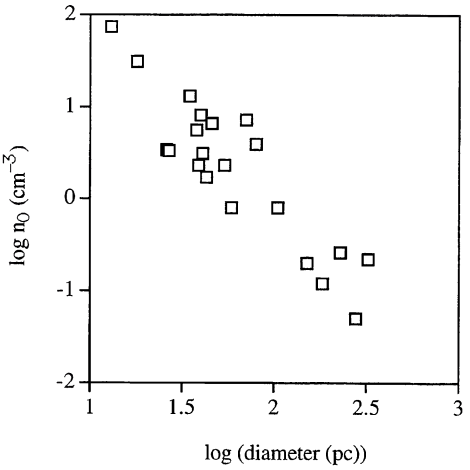


FIG. 4. The variation of local density with large *IRAS* shell diameter.

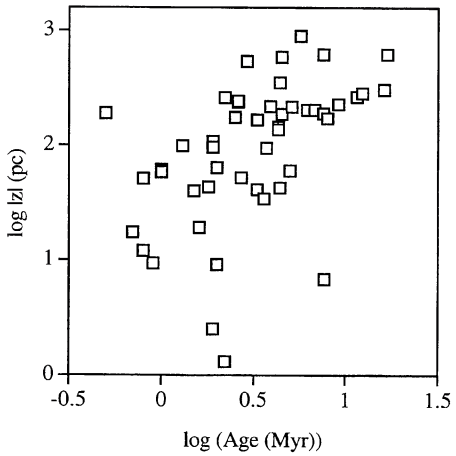


FIG. 6. Variation of shell ages with galactic height, z.

the shell surrounding WR75 (RCW104) which appear to be radiatively ionised nitrogen-rich knots ejected from the WR star. Although this may explain high-velocity features associated with single massive stars, it does not explain the existence of similar absorption velocity features associated with other stars in the neighborhood of WR stars. Instead, extended high-velocity systems may well arise in super association shells (as suggested may exist outside the large *IRAS* shell around WR136 by Nichols-Bohlin & Fesen 1993).

If the wind-blown bubble picture is correct, then the WR stars must presently reside very close to where they were created. In other words, they would need to be created in low gas density regions. However, Wood & Churchwell (1989) have shown the existence of ultracompact H II regions (UCHR), harboring newly born massive OB stars, well above the plane of the galaxy. The scale height for UCHR is 100 pc, which can be compared to 45 pc for the WR stars in our sample (Conti & Vacca 1990). The creation of WR stars, forming in UCHRs, at distances of more than 100 pc above the galactic plane is therefore reasonable.

The model associated with an O star progenitor bubble appears to fit the observational facts well. The large *IRAS* shells are of a size consistent with the observed, slow expansion velocities and have existed for a few million years, the expected lifetime of an O star progenitor. The existence of high-velocity UV absorption lines in WR spectra appears unconnected with these slowly expanding structures.

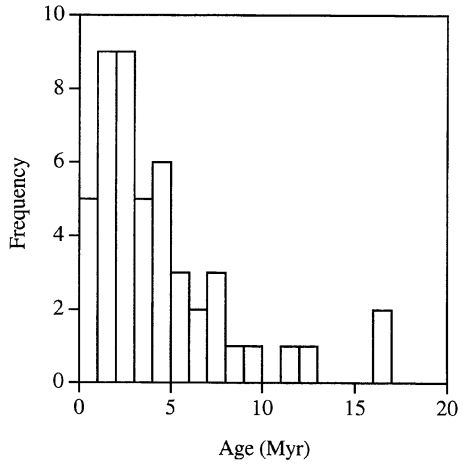


FIG. 5. The distribution of ages of progenitor O stars associated with the large *IRAS* shells.

5. CONCLUSIONS

We have presented the results of a study of *IRAS* Skyflux data associated with regions surrounding 156 galactic WR stars listed by van der Hucht *et al.* (1981). This catalog of WR stars is incomplete, as 196 WR stars are now known (van der Hucht 1996). Most of the recently discovered galactic WR stars appear in stellar clusters, so our sample is somewhat biased against WR stars in regions of high densities. Of the 156 stars observed, 49 show evidence of large ($>20'$) shells. For objects above a galactic latitude of 2°, the detection rate of large *IRAS* shells rises to over 60%. The frequency of observation of the new *IRAS* shells, particularly the sharp increase in the detection rate of shells around WR stars at higher galactic latitudes, suggests such large shells are quite ubiquitous, and only confusion with other sources and the galactic background of cirrus prevent a higher rate of detection in the plane of the galaxy. In 14 cases we find the *IRAS* shells coincident with previously observed H I shells. The central location and, in the 14 cases associated with H I shells, the kinematical association of the *IRAS* shells with the central WR stars precludes line of sight coincidence for the majority of the shells. The existence of high-velocity features, seen in UV absorption lines towards WR stars (Nichols & Fesen 1994), and sometimes seen in the spectra of neighboring stars, appears to have little correlation with the existence of a large *IRAS* shell associated with the WR star. The origin of these absorption features may be in larger super association shells (as suggested by Nichols-Bohlin &

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Fesen 1993, for the UV absorption lines in WR136 and nearby stars).

The most likely origin of the large *IRAS* shells is the wind-blown bubble of the O star progenitor, although a supernova shell or a shell created from ejected mass from a compact companion during a RLOF have been suggested as origins for two previously known large *IRAS* shells (Nichols & Fesen 1994). However, only two of our *IRAS* shells surround pulsars and in each case the pulsar is considered to be at a very different distance to the WR star. The shells, in these cases, may be foreground or background SNRs. No large *IRAS* shells surround both a WR star and a pulsar (although an H I shell around a WR star and pulsar has been observed by Arnal & Mirabel 1991). It therefore appears as if there is no direct relation between the existence of the large *IRAS* shells and a supernova event. The likely percentage of WR stars with compact companions is also much lower than the observed large *IRAS* shell detection rate. This makes it unlikely that there are enough compact companions to WR stars in order for ejected mass from a RLOF to produce many, if any, of the large shells observed. The measured (and estimated) timescales for the expanding shells are too long for either the supernova or binary ejection models to work.

The cool outer rings produced in the O star phase of a WR have rarely been observed optically (only 8% of WR stars in a southern galactic survey show optical emission-lines which may be associated with the O star progenitor shells; Marston 1996). The low temperature and large apparent sizes make them more easily visible in the *IRAS* data. Marston (1995b) has suggested that progenitor O star ring sizes may be used to estimate the ages of the central stars. Using similar assumptions, total ages of the 48 stars with associated O phase rings range from 0.5 to 16 million years (the *IRAS* shell around WR11 is almost certainly from an ejecta phase as it coincides with the optically observed ejecta shell; Marston *et al.* 1994b). The extreme values in ages are associated with shells for which an expansion velocity is not known and are likely to be uncertain by factors of 2. We conclude that our results are consistent with current estimates of the O star lifetime of single WR stars (Maeder & Meynet 1994).

One consequence of associating *IRAS* shells with the O star phase is that, in order to remain relatively central to the slowly expanding *IRAS* shells, most WR stars must be formed close to their current position. This means producing some WR stars at heights of 100 pc or more above the galactic plane. However, a number of ultracompact H II regions harboring young, massive stars exist at high galactic latitudes, and the scale height of these regions is greater than that of our WR sample. It appears likely that many WR stars have not moved far from their birthplace.

Further investigations of *IRAS* data of the regions surrounding WR stars will include a complete HIRES *IRAS* data survey of the catalog of galactic WR stars of van der Hucht *et al.* (1981). This will also allow the detection of the smaller ejecta and wind-blown shells around WR stars. The detected far-infrared shell sizes and total emission will enable the determination of the length of ejecta phases and total masses ejected by WR stars in this phase.

The overall goal of the project is to combine the far-infrared data with optical and sub-mm data to observationally determine the time periods of the various phases and total mass-loss associated with all galactic WR stars. In comparing our results with stellar evolution models, we hope to pin down the most likely means by which the galaxy's most massive stars evolve.

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