Revista Mexicana de Astronomía y Astrofísica
Universidad Nacional Autónoma de México
rmaa@astroscu.unam.mx
ISSN (Versión impresa): 0185-1101
MÉXICO

2002
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A NEW LOOK AT THE HOLES OF IC 2574
Revista Mexicana de Astronomía y Astrofísica, abril, año/vol. 38, número 001
Universidad Nacional Autónoma de México
Distrito Federal, México
pp. 39-49

Revista Mexicana de Astronomía y Astrofísica, **38**, 39–49 (2002)

A NEW LOOK AT THE HOLES OF IC 2574

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Received 2001 October 8; accepted 2002 February 28

RESUMEN

Se analizan las propiedades de los agujeros en el hidrógeno neutro y de las cáscaras en expansión encontradas en la galaxia enana IC 2574, con el propósito de averiguar cuál es el modelo más satisfactorio que explique su formación. Encontramos que, además de una clara asimetría espacial en las propiedades fotométricas y en la masa de H I, hay una clara diferencia en las edades cinemáticas entre los agujeros que se encuentran en el lado de la galaxia que rota hacia nosotros ($30.0\pm^{13.0}_{10.5}$ Myr) y los del lado contrario (16.45 ± 5.0 Myr). La probabilidad de que este hecho sea casual es menor que 4×10^{-3}. Esta asimetría podría indicar que existe una conexión entre la actividad estelar y la formación de agujeros en el medio interestelar. Además revisamos cada una de las teorías alternativas propuestas y encontramos que, o bien son insatisfactorias o adolecen de problemas serios. Se concluye que la mayoría de los agujeros de IC 2574 han sido probablemente originados como consecuencia de múltiples explosiones de supernovas.

ABSTRACT

Several scenarios have been proposed to explain the existence of H I holes in galaxies. In this work, the properties of the holes and shells in the nearby dwarf galaxy IC 2574 are used to test the different models. We report that the distribution of the kinematic ages of the holes located at the receding side of the galaxy is remarkably different from the distribution for the holes situated at the approaching side. The mean values of the kinematic ages are 16.45 ± 5.0 Myr and $30.0\pm^{13.0}_{10.5}$ Myr, respectively. We estimate a probability of less than 4×10^{-3} that the age distributions were drawn at random. An asymmetry between both sides is also found in the photometric properties and in the H I mass. These results are interpreted as evidence in favor of a connection between the star formation activity and the formation of holes in the interstellar medium, in accordance with the predictions of the classical hypothesis that shells are created by multiple supernova explosions. In addition, we find that the alternative scenarios face substantial difficulties and, so far, none of them can convincingly explain the observed abundance of spherically expanding shells. After an examination of the different alternative models, we conclude that most of the holes in IC 2574 are likely the result of multiple supernova explosions.

Key Words: **GALAXIES: INDIVIDUAL (IC 2574) — GALAXIES: ISM — ISM: KINEMATICS AND DYNAMICS — ISM: STRUCTURE**

1. INTRODUCTION

There is a consensus that the star formation and the dynamics of the interstellar gas in galaxies is mainly regulated by some feedback mechanisms. In spiral galaxies, star formation is primarily concentrated within spiral arms, suggesting that a dynamical self-regulating process, which keeps the Toomre Q parameter roughly constant, is operative (e.g., Quirk 1972; Wang & Silk 1994). In galaxies lacking global triggering mechanisms such as density spiral waves, other mechanisms likely dominate; for example, star formation may be regulated by the balance between stellar energy injection and cooling in a cloudy multiphase medium, which may suffer from outflows (or inflows) of gas for low-mass galaxies. Self-propagating/percolating star formation, intermittent star formation activity, or episodes of starbursts are concepts usually related to star formation phenomena in dwarf galaxies (e.g., Gerola, Seiden, & Schulman 1980; Hunter 1997).

In regions of star formation, especially in OB associations, winds from massive stars and supernova explosions (SNe) may have an important influence on the surrounding interstellar medium (ISM). Shells and holes created in dwarf galaxies can grow to large dimensions (of order of 1 kpc) due to their smaller gravitational potential and lower volume density. These considerations have been exhaustively discussed by Puche et al. (1992), Walter & Brinks (1999, WB99 hereafter), and Kim et al. (1999) from H I observations of the dwarf galaxies DDO 50 (≡ HoII), IC 2574 and the LMC, respectively. Other small galaxies with abundant holes are the SMC (Staveley-Smith et al. 1997), IC 10 (Wilcots & Miller 1998) and DDO 47 (Walter & Brinks 2001). The differential size distribution of holes created by the expansion of OB superbubbles was inferred by Oey & Clarke (1997), assuming a power-law luminosity function. Their predictions fit the observations of the SMC surprisingly well.

The standard model for the creation of holes is currently being questioned and several alternative mechanisms have been proposed (see Rhode et al. 1999, and references therein). In this paper we will highlight several remarkable features of the holes in dwarf galaxies, especially those present in IC 2574, which may be very useful to discriminate between the different scenarios. The first feature is a remarkable asymmetry in the distribution of ages of the holes along the galaxy (§ 3). The second aspect, already noticed by WB99, is that most of the holes are very spherical (§5). Based mainly on these findings we discuss the implications for the different mechanisms proposed for the existence of holes (§ 6). We conclude that the SN hypothesis described by Puche et al. (1992) is consistently favored and that the majority of the expanding shells in IC 2574 were most likely produced by powerful explosion events such as SN explosions or gamma-ray bursts. We must admit that a single galaxy cannot be used to exclude completely alternative scenarios, but we feel that IC 2574 is a good prototype and can provide a new insight into the nature of the H I holes.

2. THE LOW-MASS GALAXY IC 2574. HOLES AND SHELLS

IC 2574 is a nearby gas-rich dwarf galaxy of the M81 group, located at a distance of approximately 3.6 Mpc (Freedman et al. 1994). From H I synthesis observations with the Westerbork Synthesis Radio Telescope (WSRT), Martimbeau, Carignan & Roy (1994) derived the rotation curve, the mass in H I gas ($\approx 6 \times 10^8\ M_\odot$), and the dark matter content. The inferred rotation curve rises slowly in a solid-body manner throughout the disk, reaching a maximum rotational velocity of 67 km s^{-1}. The adopted inclination was $i = 75^\circ \pm 7^\circ$ (Bottinelli et al. 1983). A more recent H I study has been performed by WB99 at high spatial and velocity resolution (95 pc $\times$ 2.6 km s^{-1}). The H I scale height was estimated to be of order of 300–400 pc. The lack of spiral density waves and rotational shear make this galaxy an ideal system to investigate the nature of holes. All these authors emphasize the connection between the Hα emission and the H I distribution; most of the H II regions are located on the rims of H I holes (see also Stewart & Walter 2000).

For our study, we have taken advantage of the catalog of 48 holes reported by WB99. This catalog is intended to be complete for holes of diameter larger than $\sim$ 100 pc, up to holes of 1000 pc. The kinematic ages were assigned for an adopted distance, D, of 3.2 Mpc. As the hole diameter scale linearly with D, the ages also scale in the same fashion. Since our study is based on the relative values of the kinematic ages, and not on their absolute values, the results and the line of argument presented in this paper will be valid regardless of the adopted value for D.

WB99 also present a thorough study of the statistical properties of the holes of IC 2574 and make a comparison with those found in M31, M33, and DDO 50 (see Oey & Clarke 1997 for the SMC). For the purposes of this paper, there are a few results that deserve emphasis: (1) the distribution of energies of SNe needed to create the observed H I holes are similar for the four galaxies under consideration, (2) the histogram of the distribution of the ages in dwarf galaxies are flatter than for the spirals. In fact, the distribution of ages for DDO 50 is rather flat and spans up to 120 Myr, whereas the hole ages for M31 and M33 are clearly concentrated within the interval 0–20 Myr (between 85–95 percent of the holes lie within that interval). Conversely, the hole sizes are larger in dwarf galaxies than in spiral galaxies on average. These facts suggest that holes are destroyed more rapidly in spirals by the combined effect of shear and mixing due to density waves (WB99). Since IC 2574 lacks shear and density waves, holes may grow for a longer time without significant distortion. A major difference of the holes in IC 2574 compared to spiral galaxies is that over 90 percent of them are very round in shape.

Puche et al. (1992), WB99 and Kim et al. (1999) conclude that all the features described above, the observed radial expansions, energy requirements, as well as the kinematic ages of the holes, are fully consistent with the standard SN scenario (e.g., Tenorio-Tagle & Bodenheimer 1988).[1] In the next section we go a step further in the statistical analysis of the holes in IC 2574, in order to check the robustness of the different mechanisms proposed for the origin of holes. We think that any scenario for the existence/formation of holes should account for all observed features to complete satisfaction (see § 6). Although not all the holes need to have the same origin, it is essential to test and quantify the relevance, and difficulties, faced by alternative hypotheses.

Throughout this paper we will refer to each hole by its associated number, as given in WB99. We also divide the holes into the types 1, 2, and 3, according to the classification of Brinks & Bajaja (1986). Type 1 holes are holes that lack detectable H I emission at any velocity, and probably correspond to total blowouts. Type 2 holes correspond to holes that are offset with respect to the plane of the galaxy, whereas type 3 holes are the classical holes, with clear double-peaked profiles.

3. A REMARKABLE ASYMMETRY IN THE AGE DISTRIBUTION OF THE HOLES IN IC 2574

Here we propose to explore the asymmetry, in the average properties (see below), between the approaching and the receding sides of IC 2574. Our aim is to see whether the holes also reflect some kind of asymmetry that could give some clues on their origin.

Evidence of an asymmetry can be observed both in the low resolution integrated H I map and in the global profile at 21 cm (cf. Fig. 4 of Martimbeau, Carignan, & Roy (1994) and Figs. 4 and 5 of WB99), implying that there is more H I on the approaching side than on the receding side. The second and more intringuing asymmetry appears in the R-band image. In this band, the emission on the receding side is stronger than on the approaching side. This fact is indicative of an asymmetry in the old stellar population. Furthermore, from the Hα image reported in WB99 (see also Miller & Hodge 1994), we find that the receding side contains more than twice as many H II regions as the approaching one.

[1]Rhode et al. (1999) have questioned this scenario since they failed to find remnant stellar clusters at the centers of several large holes in DDO 50.

Taken together, it turns out that there exists a clear asymmetry between both sides of IC 2574, and probably a more intense star forming activity on the receding side of the galaxy during its recent past history. If the formation of holes is related to massive star formation, an asymmetry in the latter is likely to be reflected in the properties and/or distribution of the observed holes. If this holds true, this would favor the hypothesis that the holes are due to the injection of energy from SNe. We are now in a position to look for any asymmetric property in the holes of IC 2574. The kinematic age of the holes, defined as $t_{\rm age} \equiv d/2v_{\rm exp}$, where d is the hole diameter and $v_{\rm exp}$ the observed expansion velocity, is the most natural choice to be considered, at least initially, as young holes are expected to be found preferently in regions of recent star formation.

We divide the holes into two groups: those located at the receding side (RSG, hereafter), and those at the approaching side (ASG). Hole 22 is excluded in the analysis as it coincides with the apparent minor axis. The holes which are stalled, or which correspond to total blowout, and which therefore have no associated kinematic age, are not considered (an attempt to include these holes in the statistics is discussed below). As mentioned above, the purpose of this separation is to check whether holes comprise a homogeneous population. The existence of any asymmetrical property between the holes in RSG and ASG would be interesting and would need an explanation even if the galaxy were perfectly symmetrical in the kinematic, morphological or photometric properties. In principle, one could look for an asymmetry between any two arbitrary halves of the galaxy. In particular, for galaxies with low inclinations, there should be no preference to split the galaxy in halves along any particular line. A cursory inspection of IC 2574 suggests an asymmetry between the two halves defined by the minor axis (as is shown below, no such asymmetry is apparent with respect to the major axis) which is why in the analysis presented here we stuck with the most obvious choice. For galaxies with high inclinations (like IC 2574), an asymmetry with respect to the apparent minor axis rather than with respect to the major axis is expected, because disks are more responsive to perturbations leading to asymmetries, or even lopsidedness, along the disk.

In Figure 1, we plot in the form of histograms the distribution of ages for RSG and ASG, separately, with the caveat that we are dealing with low number statistics. The number of holes in each group is comparable (16 holes in RSG and 14 in ASG). An inspec-

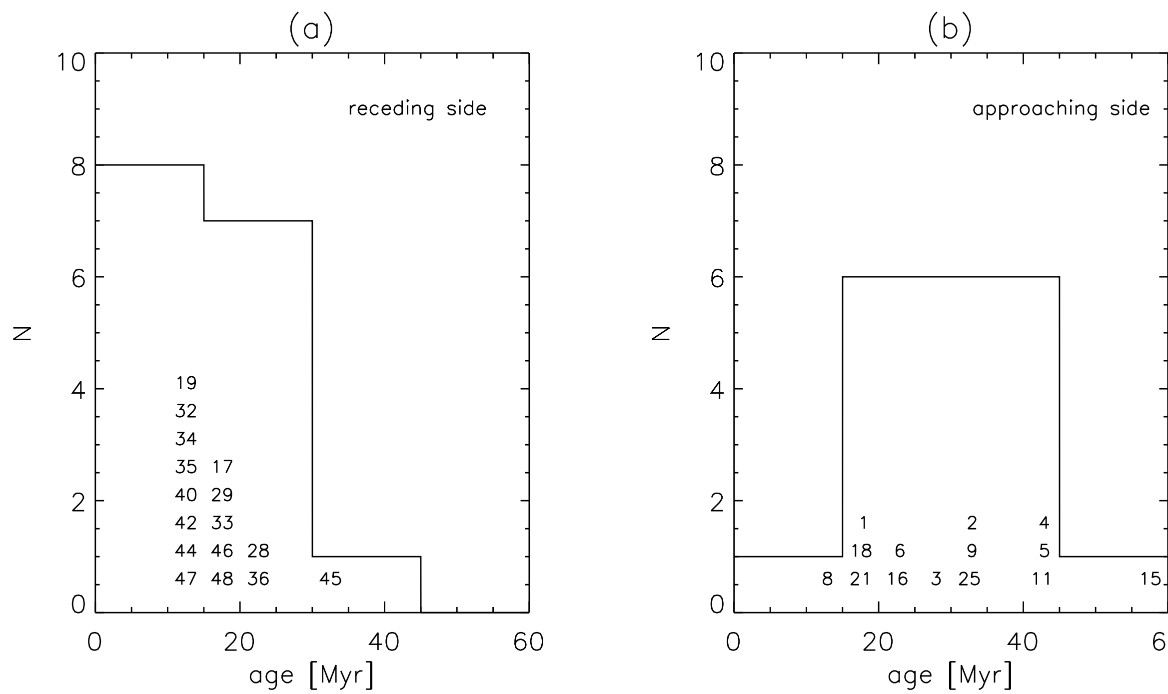

Fig. 1. Number distribution of kinematic age for holes (a) on the receding side, and (b) on the approaching side. In each graph the numbers of the corresponding holes binned at intervals of 5 Myr are shown to allow construction of histograms at different bin sizes. Owing to the low number statistics, a bin size of 15 Myr seems a reasonable compromise.

tion of Fig. 1 shows a notable difference between the two distributions. The H I shells in RSG are concentrated around an age of 15 Myr with the oldest being 30.2 Myr. The age distribution for holes in ASG is flatter (larger dispersion). The mean values for the ages of the holes are 16.45 ± 5.0 and $30.0^{+13.0}_{-10.5}$ Myr, for RSG and ASG, respectively. Interestingly, RSG contains only one hole older than 25 Myr, whereas there are eight such old holes in ASG.

Different tests of its significance have been carried out. First, we wish to decide whether the evidence indicates a significant difference between the means. We find a probability 8×10^{-4} that the samples came from normal populations with the same mean and variance. We have used that the variable u defined as:

$$u \equiv \frac{|\bar{t}_{\rm R} - \bar{t}_{\rm A}|}{(S_{\rm R} + S_{\rm A})^{1/2}} \left(\frac{n_{\rm R} n_{\rm A} (n_{\rm R} + n_{\rm A} - 2)}{n_{\rm R} + n_{\rm A}} \right)^{1/2} , \quad (1)$$

where the subscripts R and A stand for the samples RSG and ASG, respectively, follows the t-distribution with $n_{\rm R} + n_{\rm A} - 2$ degrees of freedom (Kendall 1955; Kendall & Stuart 1977). Denoting by I either R or A, $\bar{t}_{\rm I}$ is the mean of the sample 'I', $n_{\rm I}$ the number of holes and $S_{\rm I}$ the sample sums of squares about the mean. The application of "con-

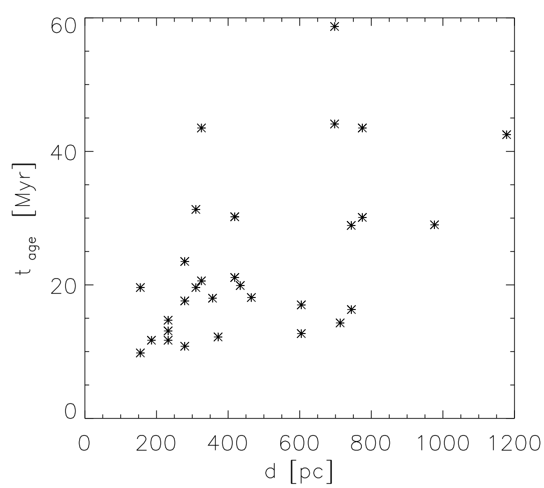

Fig. 2. Kinematic age versus diameter for the H I holes in IC 2574.

ditional distributions" is recommended if one wishes to relax the hypothesis of normal populations. In this respect, the modified Pitman test gives also a probability 8×10^{-4} that the observed difference was arrived at by chance. If observational errors of 20% are included, this probability could be increased up to 2×10^{-3}. Furthermore, both the χ^2 and the Kolmogorov-Smirnov tests estimate even smaller values for it, probably because they are less sensitive when samples are very different. In conclusion, we infer that, whatever the reason, the differences in kinematic ages between both populations cannot be accounted for on the supposition that the distributions are arrived at by chance from the same population.

For comparison, similar tests were performed for an "orthogonal" division of the galaxy, i.e., in two halves delineated by the major axis. These tests estimate a probability of 0.32 that both samples came from the same population.

In the following, we consider how the tests of significance are affected if our sample is extended under some criterion to be specified.

The "extended" sample of holes is as follows. As suggested by the positive trend between d and $t_{\rm age}$ shown in Figure 2, we assume that those holes with $d \gtrsim 700$ pc are older than 30 Myr; with the exception of the holes 13, 23, and 26, because there is evidence that they are a superposition of several holes. Conversely, shells with diameter $d < 200$ pc are probably young (i.e., $t_{\rm age} < 15$ Myr). In particular, hole 31 ($d = 180$ pc) is included as a young one. The fact that this hole presents Hα emission on its rim reinforces our conjecture. The following seven (out of 48) holes are still discarded in the extended sample: 24, 37, 38, and 43 on the receding side and 10, 12, and 14 on the approaching side. H II regions were found along the rim of the hole 24, suggesting that it might be young also. However, it could be an artifact due to projection effects, as it is located in a rich region, near the center of IC 2574. It was therefore not included in the sample.

Figure 3 shows the age histograms for the extended sample of holes. The difference between the age distributions is still apparent. In order to proceed further in the test of significance, an age of 33 Myr was assigned for the new holes with $d \gtrsim 700$ pc and 10 Myr for those with $d < 200$ pc. Under these assumptions, the modified Pitman test suggests a probability 4×10^{-3} for these samples being drawn from the same population. Since the assumptions made to calculate this value are rather conservative, here we will consider this probability as an upper limit.

The age asymmetry cannot be attributed to the lack of accuracy of the inferred kinematic ages, typically 20 % (see WB99). Furthermore, systematic errors in the values of $v_{\rm exp}$ between the receding and approaching sides seem unlikely to occur, inasmuch as we are dealing with H I observations at high resolution (typical error about 2 km s^{-1}). Nevertheless, identical statistical analyses were performed for DDO 50 and DDO 47 in order to explore this possibility. No statistical significance for any kind of asymmetry between the receding and the approaching sides was found for those galaxies.

As a separate test to look for a source of possible systematic errors, we explored the distributions of $v_{\rm exp}$ for RSG and ASG, separately (see Figure 4). The mean values are very similar, 10.5 and 11.6 km s^{-1} for the RSG and ASG, respectively, and no significant statistical differences were found in their distributions. All these tests together lead us to conclude that there is no indication that the kinematic ages suffer from systematic errors in their determinations.

The age asymmetry may put some constraints on the different scenarios proposed for the origin of holes in dwarf galaxies. In the following section, a possible interpretation of this asymmetry is suggested within the classical SN scenario. A discussion of alternative models is left to § 6.

4. INTERPRETING THE AGE ASYMMETRY IN THE STANDARD SCENARIO

In the classical scenario, holes are the result of combined stellar winds and SNe produced in young stellar associations (see Tenorio-Tagle & Bodenheimer 1988 and van der Hulst 1986 for reviews). New stars can form by self-propagation as a result of gravitational instabilities in the shocked layers. Additionally, in gas-rich dwarf galaxies, star formation may occur in violent episodes of starbursts. The gravitational interaction with a close neighbor has been proposed as a possible triggering mechanism (e.g., Mihos, Richstone, & Bothun 1992; Taylor 1997; WB99).

In this picture, the inferred age asymmetry in IC 2574 inmediately dictates that SNe (and also the underlying star formation, if the IMF does not depend strongly on the environment) should have been more abundant on the receding side than on the approaching part during the last 25 Myr. One possibility is that star formation commenced on the approaching side and propagated towards the other side. Even though there exists a slight gradient in the hole ages along the major axis, self-propagation seems to be an unlikely explanation because the typical time for self-propagation is too large compared to the age difference between holes which is

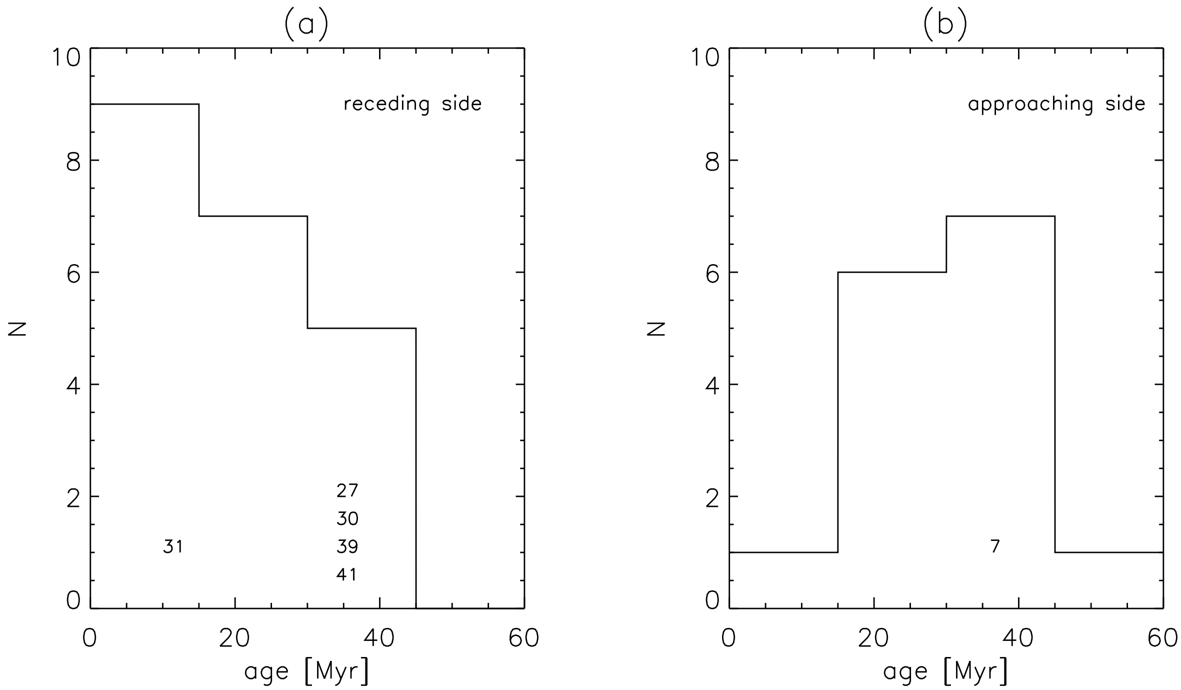

Fig. 3. Same as Figure 1 but for the extended sample of holes. Only the numbers of the added holes are quoted in the graph.

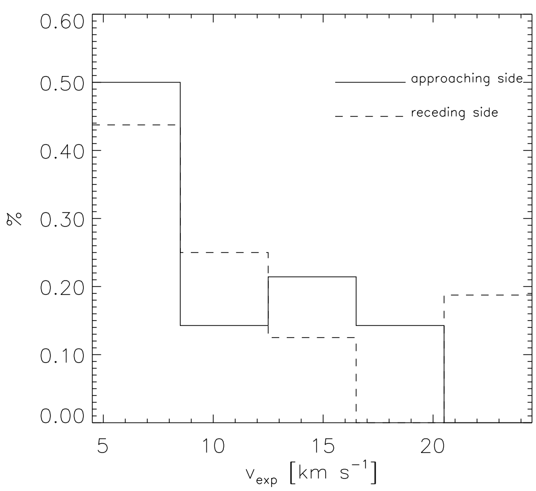

Fig. 4. Fractional number distribution of expansion velocities for ASG (solid line) and RSG (dashed line).

of $\sim$ 25 Myr. In fact, if we adopt a typical propagation velocity of 36 km s^{-1} (e.g., Dopita, Mathewson, & Ford 1985), the self-propagation timescale is $\tau_{\rm prop} = R/(36~{\rm km~s^{-1}}) \gtrsim 200$ Myr, for a typical galactic radius R of ~ 8 kpc.

A tidal encounter with a galaxy companion could have triggered star formation more strongly on the receding side. The intense star formation activity in the outer parts lends support to this hypothesis. Furthermore, the isovelocity contours are not highly perturbed (cf. Fig. 6 of WB99), suggesting that the perturbation was relatively weak. This feature also indicates that the peripheral star formation was not induced via the accretion of surrounding gas from an envelope, as occurs in IC 10 (Shostak & Skillman 1989; Wilcots & Miller 1998). The differences in the rotation curve of the approaching and receding sides observed in IC 2574 (Martimbeau et al. 1994) could be attributed to noncircular motions due to a tidal interaction (e.g., Barton, Bromley, & Geller 1999), but the expansion of giant H II regions (Martimbeau et al. 1994) or deviations from axisymmetry in the mass distribution of the surrounding dark halo (e.g., Schoenmakers, Franx, & de Zeeuw 1997) might be also responsible. The absence of holes younger than 10 Myr suggests that this galaxy is now in a post-starburst phase (see also WB99).

Tidal interactions have been shown to enhance the star formation in galaxies on both nuclear and global scales (Keel et al. 1985; Bushouse 1987; Kennicutt et al. 1987; Combes 1993; Young 1993). Since IC 2574 does not show massive star formation in the inner regions, the hypothesis that gravitational interactions with a companion are affecting the star formation of this galaxy is a bit doubful. However, three different possibilities may be suggested to overcome this objection: (1) the galaxy consumed its molecular gas in the central part in a previous interaction, (2) the gravitational encounter has distorted the dark halo of the galaxy, being able to excite internal disk modes more effectively in the outer parts (e.g., Vesperini & Weinberg 2000, and references therein), (3) for some geometries of the encounter (e.g., the relative directions of the disk rotation and the encounter orbit), not enough material is driven towards the central regions to activate massive star formation. In this sense, it is worthwhile noting that the emission of the nuclear source is not always the strongest source in interacting galaxies, e.g., the disk emission along the western edge of the asymmetric spiral galaxy NGC 2276 is over twice the luminosity of the nuclear region (Davis et al. 1997). Even more peculiar is the star formation in the interacting pair NGC 7733/7734. Jahan-Miri & Khosroshahi (2001) show that starburst activity occurs *only within the disk* of only one of the two interacting spirals. In fact, NGC 7733 presents young star-forming regions with ages in the range 1–100 Myr, but there is no evidence of starburst activity in its nucleus. We conclude that the nonexistence of massive star formation in the central regions does not rule out the hypothesis of a tidal encounter as the triggering mechanism.

5. THE DOMINANCE OF SPHERICAL SHELLS

A decisive feature to discriminate between models explaining the formation of holes and shells may be the shape of the shells. It is stunning to note that over 90 % of the holes in IC 2574 are circular in shape, indicative that they are intrinsically spherical (WB99). This is consistent with the lack of rotational shear in this galaxy. Nevertheless, other requirements need to be fulfilled in order to avoid the existence of a significant number of elliptical holes. First, there should be little chance for the merger of two neighbouring expanding shells. Second, no secondary generation of SNe should occur in shock layers with an energy comparable to that of the parent hole. Otherwise, the generation of elliptical holes would be unavoidable. More importantly, there should be also a conspiracy in the direction perpendicular to the disk, since a different expansion velocity in that direction would lead to a wide range of axial ratios.

It is important to remark that the circular morphology provides more reliable age estimates for holes than in the elliptical case. Thus this property strengthens even more our confidence in the statistical analysis concerning the age asymmetry discussed in § 3.

Palouš, Franco, & Tenorio-Tagle (1990) illustrated the stretching effect on holes due to shear and applied their results to M31 and M33. In general, little information regarding the processes that created the holes can be inferred by considering the observed axial ratios, because of the interplay of several competitive effects. For illustration, consider DDO 50 which presents holes with a wide range of ellipticities. Holes with similar age, energy and galactocentric distance do not necessarily have the same axial ratio (e.g., holes 13 and 51 with axial ratios 0.6 and 0.88, respectively). This is clear evidence that differential rotation is not the only agent to produce nonspherical holes. In the next section, we will point out that the dominance of spherical shells, at least in IC 2574, is tentative evidence in favor of the SN scenario.

6. IMPLICATIONS FOR ALTERNATIVE MECHANISMS FOR THE CREATION OF HOLES

The two features described in the previous sections, namely the age asymmetry and the circular shape of most of the observed holes in IC 2574, put strong constraints on any alternative theory for the creation of holes. In this respect, WB99 argue that there is sufficient evidence to discuss the formation of holes in terms of stellar winds and SNe, although they admit that the conventional picture is not free of potential problems. Rhode et al. (1999) have tested the conventional interpretation by looking for remnant stellar clusters at the center of the giant holes in DDO 50, and other observational evidence. At least 16 holes contain no detectable point sources and none present diffuse Hα or X-ray emission, in contrast to the predictions by the SN scenario. An explanation for the nondectection of A and F stars in the interiors of the shells is that the ages of these shells are so large that the central clusters would have been disrupted because of random motions and that their most massive stars would have evolved off the main sequence (Efremov, Elmegreen, & Hodge 1998; WB99). The lack of detection of X-ray emission is expected because the X-ray luminosity of the majority of superbubbles is well below the *ROSAT* detection limit (Brinks, Walter, & Kerp 2000, and references therein).

In this section we will try to critically examine the alternative scenarios in order to find the most satisfactory, if any.

6.1. *Impacts from High-Velocity Clouds*

The infall of high-velocity clouds from the galactic halo is a natural mechanism to explain the formation of the largest holes (Tenorio-Tagle et al. 1987; van der Hulst & Sancisi 1988; Santillán et al. 1999). Large amounts of energy can be released per event and it is indeed an appealing mechanism for the origin of holes located beyond the optical galaxy where star formation activity becomes very low. However, it is usually argued that the rate of collisions is too low in dwarf galaxies to explain all the observed holes. As an example, Rhode et al. (1999) found only a single candidate cloud in the halo of DDO 50.

Cloud collisions would form shells with a "bullet-hole" geometry and can hardly account for the formation of holes of type 3, or the abundance of intrinsically spherical holes in those galaxies with comfortably high inclinations (as IC 2574). In addition, if clouds fall randomly on the gas disk, it is difficult to explain convincingly the age asymmetry. The probability, which is already small, that all the holes were created by collisions should be decreased by a further factor of $\sim 10^{-3}$ to match the age asymmetry.

6.2. *Instabilities in the Disk*

A very intuitive way to create simultaneously regions of low density (cavities or holes) and regions of high density is through evacuation of gas by the action of thermal or gravitational instabilities. Two different possibilities are discussed in the literature, hole formation by gravitational fragmentation of a cold disk (Wada, Spaans, & Kim 2000) or holes as the result of the fragmentation of spiral arms (Crosthwaite, Turner, & Ho 2000). These alternative explanations are discussed separately in the next subsections.

6.2.1. *Gravitational Instabilities in the Disk*

Based on two-dimensional simulations, Wada et al. (2000) have recently proposed that holes and cavities form continuously in the ISM due to the non-linear nature of the multiphase medium, which is subject to both gravitational and thermal instabilities, without invoking SN explosions. A detailed discussion of conceptual problems and other substantial difficulties faced by this scenario is given in Sánchez-Salcedo (2001). Nevertheless, it is still interesting to check whether this scenario is able to explain the age asymmetry and the roundness of holes.

In the simulations presented by Wada et al. (1999; 2000), the density substructure is generated by the action of gravitational instabilities, aided by cooling. Without star formation feedback, gas is evacuated efficiently from low-density regions, forming giant cavities ($d \gtrsim 1000$ pc). In this process of disk fragmentation, cold dense gas concentrates in filaments along the equatorial plane of the galaxy, forming mostly two-dimensional structures; *shells are not formed at all in this scenario*. For a visualization of the three-dimensional case we refer the reader to Wada (2001). This means that for galaxies with high inclination angles, there should be no chance to see circular shells. In the case of face-on galaxies, two-dimensional simulations show that cavities have any shape but circular (Wada & Norman 1999; Wada et al. 2000; Sánchez-Salcedo 2001), as expected for the evolution of a disk subject to gravitational instabilities, which are forming clumps and filaments with random (planar) motions and complicated mutual interactions. This feature becomes a fatal problem for this model.

Any discussion in terms of the ages of the holes is very puzzling in this scenario. The model assumes that massive star formation and SNe do not dominate the dynamics and formation processes of density structures. In such a situation, the initially gravitationally unstable disk overstabilizes itself on a typical timescale of 10^8 yr by increasing the radial cloud-to-cloud velocity dispersion (Wada & Norman 1999; Wada et al. 2000). Galaxies with lifetimes of several Gyr should have achieved this regime, and should present a very chaotic velocity field, making it meaningless to attribute an expansion velocity or age to low-density regions ("hole"). In other words, there is little chance to find *filaments* with coherent mass-accretion. Only in the unlikely situation that the galaxy is still in the gravitationally unstable phase (the Toomre Q parameter being less than 1), "chance" coherent evacuation of gas could be detectable. However, the requirement $Q < 1$ implies a gas velocity dispersion less than 2 km s^{-1} and, correspondingly, too small an H I scale height, < 30 pc (Sánchez-Salcedo & Hidalgo-Gámez 1999), in sharp contrast with the observed mean dispersion of 7 km s^{-1}. Furthermore, for the cooling functions adopted by Wada et al. (1999; 2000), filaments around cavities should show low velocity dispersions as a consequence of overcooling in dense regions. WB99 report the opposite behaviour for the shells in IC 2574; values of the velocity dispersion are higher where two or more shells overlap.

For a disk with radially decreasing density, the gravitational instabilities will grow faster in the inner part, where the surface density is larger, than in the outer regions. In order to have either peripheral star formation, or an asymmetry between the receding and the approaching sides, or both, as seen in IC 2574, this model also requires an external perturbation to trigger the gravitational instability. In such a situation, instead of looking for an asymmetry in $t_{\rm age}$, which has little meaning in this scenario, one would expect a more conspicuous asymmetry in both the size of the holes and gas density within the holes. The reason is simple, in those regions where the gravitational instability has developed further, evacuation of gas should be higher, leading to the generation of larger cavities of lower density. Since the H I density in the interiors of holes is below the threshold for detection, we restrict ourselves to checking the prediction of the existence of a size asymmetry. After an inspection of the diameter distributions of shells in RSG and ASG, no appreciable statistical difference between both sides was found regarding their sizes.

In the same vein, the observational relation between the density in the close vicinity of the shell, $\rho_{\rm HI}$, and the expansion velocity: $\rho_{\rm HI} v_{\rm exp}^2 =$ constant, for the holes of IC 2574 and DDO 50 (Shchekinov et al. 2001) is difficult to explain if holes are forming by gravitational instabilities. In summary, we conclude that the age asymmetry and the shape of the holes in IC 2574 have either no feasible interpretation in this scenario, or are out of line with its predictions.

6.2.2. *Holes as Byproducts of Fragmentation of Spiral Arms*

Crosthwaite et al. (2000) have observed the H I structures in the almost face-on galaxy IC 342. They claim that some of the holes in the outer disk that do not show evidence of expansion ('type 1' structures defined by Brinks & Bajaja 1986), may be voids in between self-gravitating arm segments. This is a natural and attractive explanation for the existence of holes in galaxies with delineated spirals but cannot be the case for holes in DDO 50 and IC 2574, which lack any appreciable spiral arm.

We should stress that the proposal by Crosthwaite et al. (2000) is not equivalent to the model described by Wada et al. (2000). In the simulations of Wada et al., holes arise due to evacuation of gas as the result of strong gravitational instabilities ($Q < 1$) that are able to fragment the disk into clumps and filaments, helped by efficient cooling. No spiral waves are supported in such a disk (e.g., Shlosman & Begelman 1989; Gammie 2001), but only sheared filaments. This makes a clear difference between both models.

6.3. *Turbulent Clearing*

Elmegreen (1997) pointed out that holes and gaps that make up the intercloud medium might be the result of "lacunarity" in ubiquitous interstellar turbulence. This is a very exciting possibility although there is no quantitative estimate yet or definitive numerical evidence to compare with observations. We think, however, that coherently expanding structures in turbulent media are probably not abundant enough to account for the large number of holes seen in DDO 50 and IC 2574 (see WB99 for a discussion). Holes without kinematic signatures of expansion are indeed the best candidates for turbulent clearing formation. Yet, bear in mind that some of those holes must still correspond to stalled shells created by multiple SN explosions (Oey & Clarke 1997).

6.4. *Pockets of Ionized Gas and Ram Pressure Stripping*

Holes of type 1 located in the outer parts of the galaxy could correspond to pockets of gas ionized by the intergalactic UV radiation (Rhode et al. 1999). Ionizing UV photons could keep the gas at high ionization fractions if the scale height of the gas disk is significantly larger than in a typical normal galaxy. This condition is probably fulfilled for some dwarf galaxies. One of the predictions of this model is that holes in the outer parts should be preferentially of type 1. Unfortunately, this is not the case, at least, for IC 2574. Although we recognize that a single galaxy is not enough to undermine the different scenarios, which may be operative in particular cases, we believe it can provide new constraints to the relevance of each invoked process at least in shell-filled galaxies.

Motivated in part by the simulations of Quilis, Moore, & Bower (2000), which show the process of gas stripping of SO galaxies in clusters, Bureau & Carignan (2001a,b) suggest that ram pressure stripping provides a mechanism to enlarge pre-existing holes. If this is true, ram pressure would act not only upon outer holes, but also upon any pre-existing low-density hole within the disk. Since the surface density of gas only varies a factor of 3 across IC 2574, a dominance of shells with a "bullet-hole" geometry, i.e., mainly holes of type 2, should be expected in this model. However, very few holes of type 2 have been reported for IC 2574 (only 6 holes out of 48), and for DDO 47 (3 out of 19).

Another potential shortcoming of this model is the need for a kind of fine-tuning between the ram pressure and the ISM pressure, in order for ram pressure to be able to erode pre-existing holes without significantly affecting the overall H I kinematics (i.e., the isovelocity contours). This requirement can be expressed by the following two conditions (Gunn & Gott 1972; Abadi, Moore, & Bower 1999)

$$\rho_{\rm IGM} v_{\rm rel}^2 > 2\pi G \Sigma_{\rm tot} \Sigma_{\rm g} \text{ (at the hole)}, \qquad (2)$$

and

$$\rho_{\rm IGM} v_{\rm rel}^2 \ll 2\pi G \Sigma_{\rm tot} \langle \Sigma_{\rm g} \rangle \ , \qquad (3)$$

where $\rho_{\rm IGM}$ is the density of the intergalactic medium, $v_{\rm rel}$ is the relative velocity of the galaxy with respect to the intergalactic medium, $\Sigma_{\rm tot}$ the total surface density of the galaxy, $\langle \Sigma_{\rm g} \rangle$ the mean surface density of gas in the disk, and $\Sigma_{\rm g}$ in the first equation is the surface density evaluated at the position of the hole. In these equations, the ram pressure, $\rho_{\rm IGM} v_{\rm rel}^2$, is compared with the ISM pressure of the galaxy, $2\pi G \Sigma_{\rm tot} \Sigma_{\rm g}$. For ram pressure stripping to be operative, the pre-existing holes must already be of order of $d \gtrsim 2h$ in order to satisfy Eqs. (2) and (3). Hence, this scenario would still require energy input from the combined action of stellar winds and SN explosions to sweep the gas at scales of $\sim 2h$, typically 600–800 pc for IC 2574.

Moreover, ram pressure stripping will efficiently evacuate gas from the pre-existing hole according to Eq. (2), but will be very inefficient to enlarge its size if Eq. (3) is satisfied. Our prediction is that the effect of ram pressure stripping in gas-rich dwarf galaxies would contribute only to the evacuation of gas from the large cavities already formed by other agents. This effect of evacuation of gas would be of secondary importance and does not seem to alleviate any of the potential problems usually attributed to the SN scenario. We are performing numerical studies of the process of ram pressure stripping to see whether our caveats are well-founded or not (Sánchez-Salcedo, in preparation).

7. SUMMARY

The formation of H I holes in shell-filled galaxies is most commonly attributed to multiple SN explosions occurring within wind-blown shells. This model, however, is not free of potential problems and alternative scenarios have been proposed in the literature. We have devoted our study to the properties of the holes observed in the dwarf galaxy IC 2574. Interestingly, this galaxy rotates as a solid body and does not show any evidence of spiral density waves.

Motivated by the existence of an asymmetry in the photometric properties, as well as in the H I mass, between the receding and the approaching sides of IC 2574, we have looked for a possible asymmetry in the ages of the holes. The existence of such an asymmetry would be corroborating evidence in favor of a link between star formation activity and the formation of H I holes. Our expectations were confirmed; we have found that the mean age varies from 16.45 ± 5.0 Myr on the receding side to $30.0\pm^{13.0}_{10.5}$ Myr on the approaching side. With the caveat of dealing with low number statistics, we estimate a probability of less than 4×10^{-3} that the age distributions were drawn from the same population.

The second feature that has attracted our attention is that most of the holes are intrinsically spherical, as emphasized by WB99. We have proposed that the age asymmetry and the roundness of the holes in IC 2574 may give new insight into the question of their formation.

We have critically examined the different possibilities. Impacts of high velocity clouds, which are thought to be too scarce to account for the totality of the holes seen in shell-filled galaxies (e.g., Rhode et al. 1999), can hardly account for the dominance of spherical holes observed in IC 2574, nor the age asymmetry. The scenario suggested by Wada et al. (2000), in which holes are formed due to the nonlinear evolution of the multiphase ISM, is riddled with substantial difficulties. The existence of so many expanding holes casts doubts on the process of turbulent clearing and on the hypothesis that holes correspond to pockets of ionized gas. The role of ram pressure stripping as a mechanism to enlarge pre-existing holes also remains unclear. A potential problem is the need for certain fine-tuning between the stripping pressure and the ISM pressure. Much work is required to test the viability of this hypothesis. In summary, we conclude that the classical SN scenario (including gamma-ray bursters) is still the most attractive possibility, at least for shell-filled galaxies. The age asymmetry could be consequence of a more intense star formation activity on one of the sides due to a near passage of a galaxy companion.

It is a pleasure to thank A. M. Hidalgo-Gámez, X. Hernández, and E. Brinks for helpful discussions. A deep and thorough scrutiny by an anonymous referee helped to improve this paper. This work was supported by a CONACyT postdoctoral grant and has benefitted from resources of the CONACyT project 32139-E granted to L. Binette.

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