PROCEEDINGS OF SCIENCE

HII region studies with the WSRT

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50 Years Westerbork Radio Observatory, A Continuing Journey to Discoveries and Innovations
Richard Strom, Arnold van Ardenne, Steve Torchinsky (eds)

Chapter 13 HII region studies with the WSRT[1]

Frank Israel*

1. Making plans

Well before the official opening of the WSRT, astronomers in The Netherlands were already considering how to put the powerful new telescope to good use. Many of them, with Oort in the forefront, were eager to expand their observing horizons beyond the boundaries of the Milky Way galaxy, until then the effective limit of almost all Dutch astronomical research.

These early ideas can be traced in a number of Synthesis Radio Telescope Project internal technical reports (ITRs). In the years 1967 and 1968, five of these[2] deal with possible observing programmes, and Oort provided an inventory of 15 worthwhile programmes in ITR-74, only four of which were Galactic. In part of ITR-65, Van Woerden briefly discussed HI line measurements of Galactic clouds and globules, but the only one specifically focusing on Galactic objects is ITR-48[3] by Brouw, Habing, Pottasch, Tolbert, and Van Woerden. The authors were all located at the Kapteyn Lab in Groningen, except Brouw who together with Habing was yet to obtain his PhD. The five topics were polarization, supernova remnants, planetary nebulae, HII regions, and the Cygnus-X region. Remarkably, Habing did not write the section on HII regions (which he later studied with the WSRT) but supernova remnants (which he did not). Instead it was Tolbert who discussed three lines of investigation: mapping of individual HII regions and studying early star formation; tracing Galactic structure using recombination lines, and mapping the HII region population in other nearby galaxies (among them M 33 and M 101). Before 1975, all three had been carried out with the WSRT.

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1 This is a personal account of work with the WSRT in the first five years of its operation. A detailed overview of these results and their scientific context can be found in Habing & Israel, 1979 Annual Review of Astronomy and Astrophysics, Vol. 315, p. 345. A much more complete and broader treatment of how we came to learn about star formation and the role of HII regions can be found, among other places, in the book by H.J. Habing, 'The Birth of Modern Astronomy 1945-2015' published by Springer, New York, 2018/2019.

2 ITRs 44, 48, 49, 65, 73

3 Undated, but must be second quarter of 1967

2. Flags on stellar construction sites

HII regions were of particular interest because they flagged sites of recent star formation, and thus might provide a clue as to how stars form. The most massive and luminous stars so rapidly consume their nuclear fuel that they never grow old and are always young, so to speak. As they are also very hot, they radiate intense ultraviolet (UV) light in all directions and thereby ionize the surrounding HI into ionized hydrogen (HII). This process had been elucidated many years earlier by Strömgren (1939) in a classical paper that established the fundamental relationship of HII regions to massive young stars. The ionized volume, hence the size of the HII region, depends on the flow of UV photons from the star that maintains the ionized state of the gas. In a homogeneous HI gas, the isotropic UV photon flux should create a spherical HII region, the so-called Strömgren sphere. As foreground dust clouds absorb nebular light, observed nebular shapes could be quite different. This all made a lot of sense and the only thing left to do was to determine how dense stars form out of tenuous HI gas.

This was still very much a mystery at the time. Observations in the 21-cm line readily established that the Galaxy was full of neutral hydrogen (HI) clouds. Cores in these clouds would somehow contract into stars. For a while, it was speculated that the so-called Bok globules, seen silhouetted against distant stars or bright nebulae, were isolated cores ready to collapse into stars. When looked at more closely, they seemed to be very stable, however. HII regions were more promising, albeit in an indirect way. Wasn't it reasonable to expect stars to be also forming today where they formed yesterday? Shouldn't the present-day properties of HII regions tell us about yesterday's formation of their exciting stars?

Such HII region studies were rather few and limited in scope. Dust extinction impeded global structure studies. Most attention had been lavished on eye-catching luminous nebulae many of which had already been noted by Messier two centuries earlier, such as the Lagoon nebula (M 8), the Omega nebula (M 17) and the Orion nebula (M 42). In his Galactic Plane survey, Westerhout (1958) had measured the radio emission from these and other nebulae. The radio observations were not hampered by extinction, and some of the nebulae he found, such as W49 and W51, were completely obscured by dust and optically invisible. Unfortunately, the half-degree beam of the Dwingeloo telescope showed only the largest nebulae and did not provide any useful detail. Some ten years later, just before the advent of aperture synthesis telescopes such as the WSRT, the state of the art in HII region radio research was contained in a series of papers published in 1967 by Mezger and colleagues using the newly built NRAO 140-ft telescope. At a frequency of 5 GHz, they obtained a resolution of 6'4, six times better than Westerhout's survey at 1.4 GHz. They were primarily interested in hydrogen recombination line measurements, but in their first paper (Mezger & Henderson, 1967) they provided the template for the analysis of subsequent HII region radio continuum observations, including the detailed equations for numerical analysis of thermal radio emission. Even with a six-fold increase in resolution, their maps of the thirteen Westerhout sources were still decidedly 'blobby', although they did reveal multiple components. Most importantly, they inferred the presence of 'compact' HII regions (size less than 0.5 pc, electron density typically 10^4 cm^{-3}) from fits to the multi-frequency radio continuum, even though these compact HII regions were not obvious in the radio maps. Mezger et al (1967) suggested that this new class of HII regions might be associated with known sources of OH-maser emission, and speculated that they were the ionized insides of 'cocoons' of gas and dust out of which the embedded O-star had recently formed.

3. Start a new field of research ...

This was the situation when the WSRT became operational in June 1970 with a clear focus on galaxies and distant radio sources. Among the first two dozen WSRT proposals only three targeted Galactic objects: the confused Cygnus-X region (W7: Baars & Wendker), X-ray sources (W13: Braes & Brouw), and indeed HII regions (W24: Israel, Habing, and De Jong). This was to be the topic of my Ph.D. program, supervised by Habing. We believed that the superior resolution of the WSRT (initially 24" at 1.4 GHz, soon followed by 6" at 5 GHz) would reveal the HII region structural detail necessary to infer how their stars formed in the first place.

When we started the project, the three of us were far from being expert in the field. Habing quickly set about to repair this, first by travelling to Bonn to meet Mezger who had become one of the MPI-directors in charge of the 100-m Effelsberg telescope at the occasion of a visit by Wynn-Williams who in turn had just finished his PhD. at Cambridge University. Using the new Mullard Radio Astronomy Observatory's One-Mile Telescope, the first operational aperture synthesis telescope, he had produced the first wonderful maps of HII regions concentrating on Westerhout sources like those before him. His *pièce de résistance* was a spectacular map of the obscured radio source W3, situated next to the optical nebula IC 1795 (Wynn-Williams, 1971) at a resolution of 6.5". This was fully 60 times better than Mezger's single-dish maps, and still almost a factor of four better than we could then accomplish with the WSRT. Green with envy we learned what could be done.

As it turned out, Mezger was more interested in recombination line studies, still beyond the WSRT capabilities, than in the continuum work we were about to embark on. Wynn-Williams was about to start a post-doc with Neugebauer and Becklin in California and redo his radio maps in the mid-infrared (Wynn-Williams et al., 1972). There appeared to be little scope for collaboration. After our return to Leiden, Habing cleverly invited some 35 experts

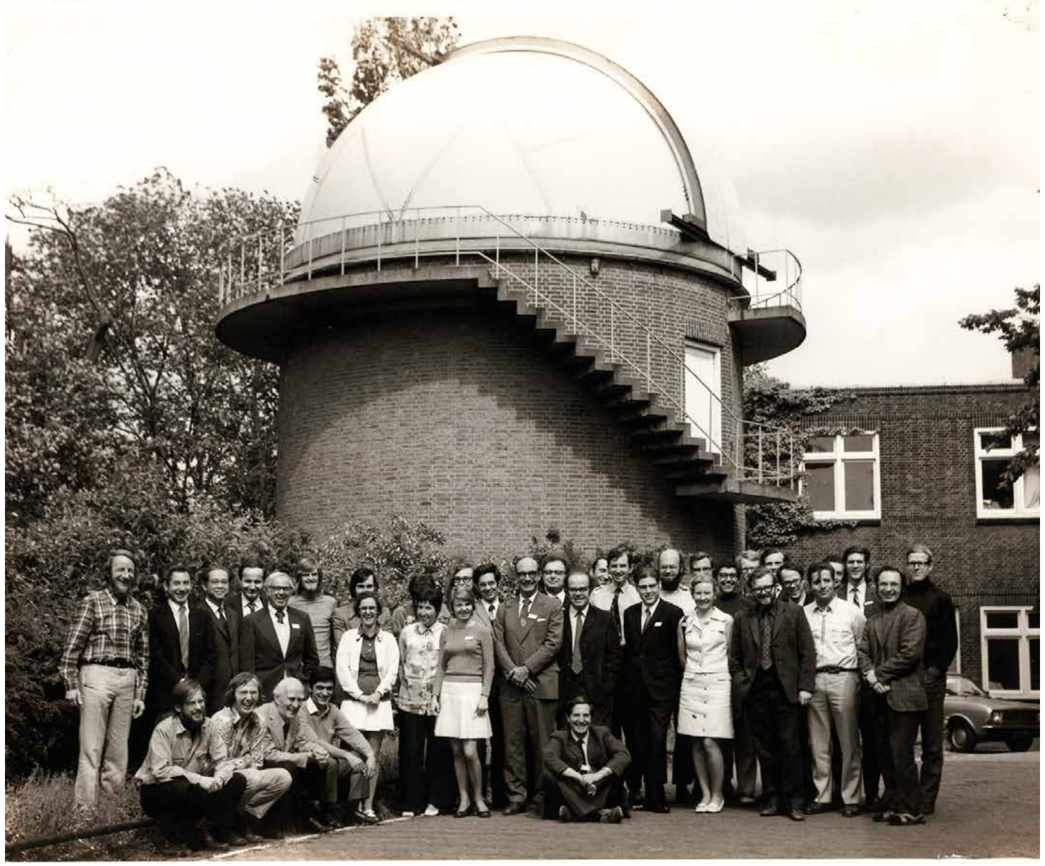

Figure. 1: Leiden, June 23, 1974. Participants of the Workshop 'The Nature of Dense Condensations in HII Regions', held at the Sterrewacht.

Front row, left to right: Frank Israel, Thijs de Graauw, Jan Oort, Nino Panagia, Lanie Dickel, Marie-Claire Lortet, Lise Deharveng, Donald Osterbrock, Franz Kahn, John Shakeshaft (seated) Heinz Wendker, Lindsey Smith, John Dyson, Peter Mezger, Stuart Pottasch.
Back row, left to right: Jaap Baars, E. Capriotti, C.C. Lin, Harm Habing, Mayo Greenberg, Vincent Icke, David Flower, unidentifiable, Piet Bedijn, Jorn Wink?, Wilhelm Altenhoff, Michael Grewing, Teye de Jong, David Hummer, Peter Biermann?, unidentified, T. Cato, unidentified, Malcolm Walmsley, unidentified, Woody Sullivan, Harry van der Laan.

Photo credit: Sterrewacht Leiden/J.F. Planken

to attend a three-day workshop on 'The Nature of Dense Condensations in HII Regions' at the Leiden Sterrewacht in June 1972. This brought us up to speed and also provided us with very useful contacts. It was the beginning of a very productive collaboration with the French optical astronomers Lortet-Zuckerman, Deharveng, and Caplan, who provided us with detailed information on nebulae and exciting stars in exchange for our radio results.

4. Intricacies of carrying out the Sharpless HII region program

Although the WSRT was not the first synthesis array telescope to take a detailed look at HII regions, it did have the advantage over the Cambridge One-Mile Telescope that it was much faster and more sensitive thanks to it having four times as many dishes, each with twice the collecting area, and seven times as many instantaneous baselines. We thus could start a program much more ambitious in terms of numbers of HII regions than our colleagues in the UK. Right at the beginning, we decided to avoid most of the Westerhout sources whose sizes are comparable to or exceeding the primary beam of the WSRT and extend well beyond the first grating response in a single 12-hr synthesis measurement. Instead, we turned to the very extensive catalog of large and small optical HII regions by Sharpless (1959). With this catalog as a guide, I spent days selecting suitable candidates (bright, and smaller than 10' in size) for observation on Palomar Sky Survey (PSS) prints. These came in two varieties: prints from red plates and from blue plates. The former highlighted HII regions as their H-alpha emission fell within the band, and the latter predominantly showed the blue exciting stars. For decades, the PSS prints and plates were among the most indispensable tools of observational astronomy. In the end, we chose about three dozen out of 313 Sharpless HII regions for observation with the WSRT.

Enthusiastic but inexperienced, we did not get off to a smooth start. It had not yet fully dawned on us that an interferometer is a great way of losing source flux, and we had failed to specify that the shortest interferometer spacing should be really short, i.e. that we required the shortest available spacing of 36 m (170 wavelengths). As the telescope group had scheduled our extended source observations for some unfathomable reason at baselines starting five times longer, the radio maps we got out of the reduction pipeline showed a lot of noise and next to no flux. In one object, we did see an intriguing chain of very weak compact sources, but later re-observation with better baseline coverage revealed that these were merely insignificant brightness fluctuations in the extended emission.

Right among the first few usable observations was a map of Sharpless 158 (S 158, also known as NGC 7538). We still missed most of the flux with a shortest baseline of 90 m but what we did see was similar to the optical brightness distribution, with the notable exception of a completely obscured, unresolved source at the southern edge of the optical nebula. An accurate position for the OH maser source detected earlier had just become available, and we found that it coincided precisely with what we imaginatively called an ultra-compact HII region (size less than 0.15 pc, electron density 10^6 cm^{-3} or higher). Combing the literature, we came up with several other cases where an OH maser was precisely coincident with a compact thermal source (Habing, Israel, & De Jong, 1972). The close association of (ultra)compact HII regions with powerful OH masers argued strongly in favor of Mezger's speculation that these objects were the actual birthplaces of young and luminous massive stars.

Almost as a curiosity, we noted a discrepancy between the radial velocity determined by optical and radio methods by as much as 10 km s^{-1}, which we did not understand, but paid no further attention to. It should have reminded us of the even larger velocity discrepancy of 16 km s^{-1} between the stars and the gas of the Orion nebula, that I had noticed as a student more than two years earlier, but we didn't realize it at the time. I remember thinking this was peculiar but nobody else seemed to think it was a big deal and I did not pay further attention to it. As it turned out, that was a mistake: never ignore discrepancies you don't understand. It should also be noted that the prototypical emission nebula, the Orion Nebula, was among the poorest possible prospects for WSRT observing. Its declination is close to zero, which means that the WSRT observing beam is extremely elongated in a north-south direction and that up to half the time individual dishes are shadowing one another. We did observe Orion A in 1973, but the map was useless even though the emission from the bright Huygens part of Orion is compact enough. A decent map was obtained only in 1976, when Martin and Gull (1976) managed to combine E-W spacings observed with the Cambridge One Mile Telescope with those from the N-S arm of the Owens Valley interferometer, and successfully clean the resulting 'dirty' map.

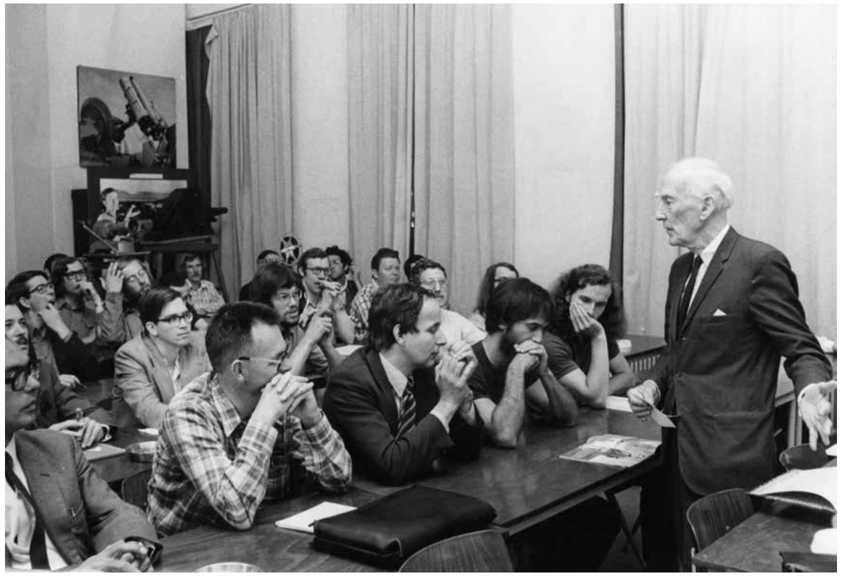

Figure 2: Leiden, August 22, 1974. Jan Oort introduces the last ever astronomical colloquium in the Sterrewacht lecture room where Alar Toomre was attempting to convince a skeptical audience that galaxies really do interact and merge. Many of the of the people depicted were actively involved in Westerbork operations and observing programs.

Front row: Luc Braes, Ernst Raimond, Harm Habing, Walter Jaffe, Edwin Valentijn.
Second row: Jean Casse, Richard Strom, Ger de Bruijn, Hans van Someren Greve, Xander Tielens.
Third row: Roelf Marten Duin, Frank Israel, Johan Degeweij, Steve Bajaja.
Fourth row: Gerard Uiterwaal, Wil van Breugel, unidentified, George Rossano. The person way in the back behind Uiterwaal might be Ron Harten.

Photo credit: Sterrewacht Leiden/L.A. Zuiderduin

My sometimes shaky technical knowledge was compensated by the generous help of Leiden colleagues such as Le Poole, Harten, and Van Someren Gréve who knew a lot more about aperture synthesis methods and reduction techniques and never tired of pointing this out. Van Someren's daily return from the university's central computing facility (CRI) with the latest Westerbork computer output never failed to fill me (and others) with apprehension. The Westerbork reduction pipeline made use of several reduction programs on thick packs of punch cards, to be run one after the other, and each to be controlled by so-called 'stuurkaarten', punch cards with instructions about map sizes and scales, contour levels, etc., provided by the user (me). I found it easy to make mistakes and hard to catch them by reading the smudgy print at the top of the cards. Van Someren had a strong sense of drama when, in front of everybody gathered for coffee, he handed out a minuscule contour map ('your postage stamp'), slowly unrolled a plot that stretched for meters because of a decimal error (`your wall-paper'), wondered publicly about the meaning of a plot containing only a single contour, or conversely, a plot with many contours squeezed together in the noise. Each of these unique products had, of course, taken up lots of computer or plotter time at the CRI.

5. Not so easy ...

Notwithstanding such minor mishaps, a significant HII region database was built up in a few years, including not only 1.4 GHz measurements but also observations at frequencies of 0.6 GHz and 5.0 GHz that in the meantime had become available, published in a number of papers, some together with other authors such as Felli, Harten, Deharveng, most of which formed the bulk of my 1976 PhD thesis. By that time it had become clear that these detailed radio maps told us a lot about HII region structure, but not so much about star formation. Clearly, when one or more luminous stars turned on and rapidly ionized their surroundings, the sudden injection of energy would wipe out almost all clues to the formation process. When fire burns down the house, not much is left of the furniture ... From HII regions we could learn how stars and gas interacted, but not what went on before. Even the obscured ultra-compact HII regions, interpreted as cocoon stars, did not reveal much about their origin.

However, this was not the end of the story. The structure of the very first HII region we closely looked at, S 158 (NGC 7538) was peculiar. Even though the radio nebula was extinction-free, and apparently excited by a single central star, it did not look like a Strömgren sphere at all. We did try to model the very asymmetrical shape by a sphere of gas containing an off-center spherical cavity. The fit was not particularly good. Moreover, we quickly found several other, mostly small, HII regions to be similarly asymmetrical and have a central brightness minimum partly surrounded by a relatively broad shell. While some of these were true windblown shells (most notably NGC 7635: Israel, Habing, De Jong, 1973; Icke, 1973; NGC 6888: Wendker et al. 1975), such an explanation was clearly not feasible for the bulk of these objects: wrong shell shape, wrong energetics. In

Figure 3

Figure 3.1: H-alpha image S 158 (NGC 7538), a small bright emission nebula. The ultra-compact HII region to its south is completely obscured.
Photo credit: Fred Calvert/Adam Block/NOAO/AURA/NSF

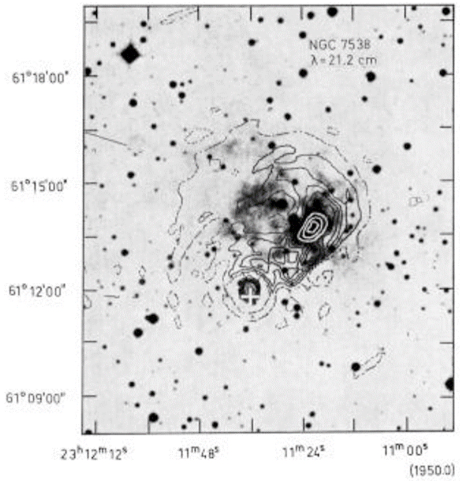

Figure 3.2: S158, WSRT 1.4 GHz, 24" resolution, shortest spacing 90m Habing et al. (1972). The extended emission of the main nebula is only partly recovered. The ultra-compact HII region is prominent. The cross marks the position of the OH maser.

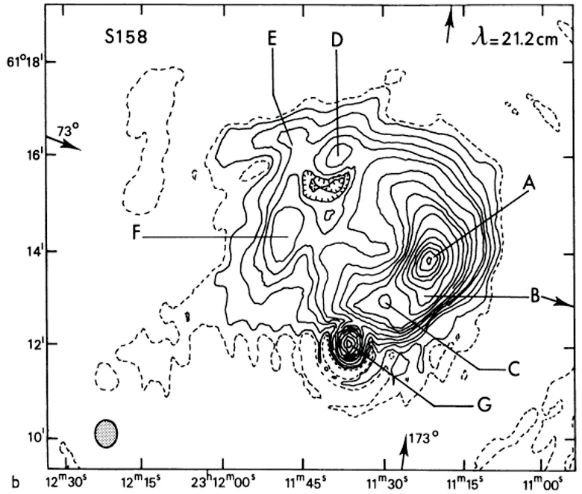

Figure 3.3: S158, WSRT 1.4 GHz, 24" resolution, shortest spacing 36m Israel (1973). The extended emission of the nebula is now fully recovered. The asymmetrical shape, relatively sharply bounded on the right, and diffuse on the left, is characteristic of a blister HII region seen more or less edge-on

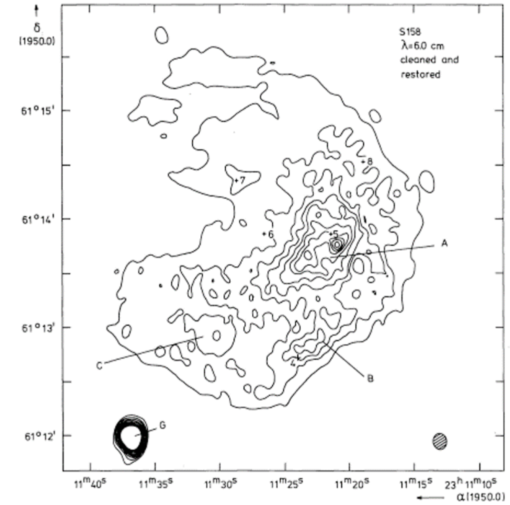

Figure 3.4: S158, WSRT 5 GHz, 6" resolution, shortest spacing 36 m. Israel (1976). The image shows more detail, but the extended diffuse emission is mostly lost. The ultra-compact HII region is still unresolved.

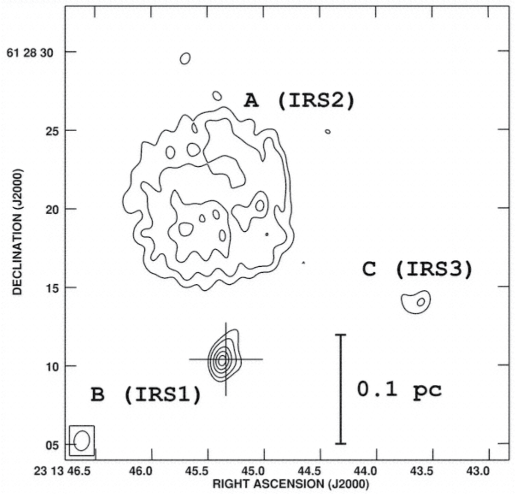

Figure 3.5: VLA B array image (resolution about 1 arcsec) of the ultra-compact object, which turns out to be a group of nebulae each surrounding a newly formed star. From Hoffman et al., 2003 ApJ, 598, 1061

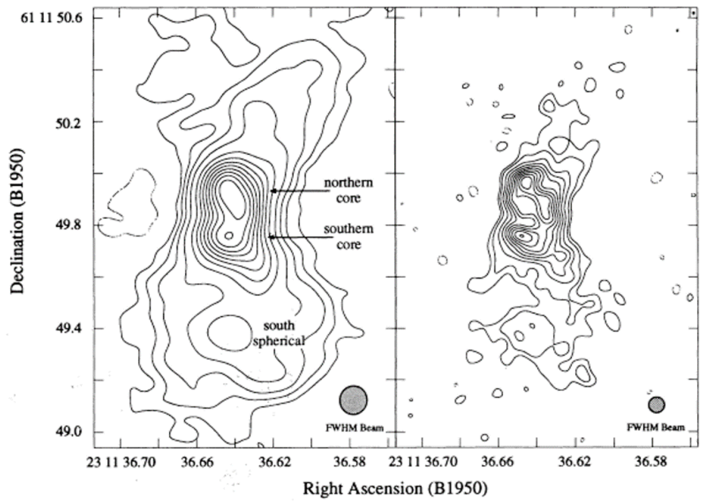

Figure 3.6: Gaume et al. 1995 ApJ 438, 776. 22GHz VLA A configuration (resolution 0."11) image of the brightest ultra-compact object component IRS-1. Even this very small object shows characteristics of a blister.

fact, also the Orion nebula has such a structure, as does Wynn-Williams' source W 3A. Although Strömgren's physical model was beyond reproof, his geometry was way off. HII regions were clearly more complex than a simple Strömgren sphere and this turned out to be true even for the ultra-compact HII regions when these were finally resolved by long baselines at short wavelengths.

This was a very puzzling phenomenon, but all attempts to get colleagues working on HII region models interested frustratingly failed. The answer came in 1974, unexpectedly, as I was leafing through a stack of preprints (no internet preprint server in those days) during a visit to NRAO in Charlottesville, USA. In one of these, Balick et al. (1974) suggested that Orion consists of flows emanating from stars embedded in a small, contracting molecular cloud behind the HII region. They also referred to an earlier paper by Zuckerman (1973) that I had overlooked, in which the Orion nebula was seen as a protrusion on a likewise small molecular cloud. These two papers hit me like a flash of lightning. Here was the vision I was looking for! Clearly, I should have paid more attention to the work of others, having ignored Orion which I wasn't studying, and rather having missed the relevance of the newly (1970) discovered molecular gas. Although Zuckerman and Balick et al. were the first to propose the connection between the ionized nebula and a previously unseen reservoir of molecular gas, they still underestimated the importance of the latter. It took three more years before the overwhelming size and mass of the Orion Molecular Cloud complex (OMC-1) was recognized by Kutner et al. (1977). Nor did the authors dare more than hesitatingly suggest that other HII regions might be similar.

6. Burning blisters

This was a major change of paradigm. The Orion nebula taught us that we had thus far tried to form stars and HII regions completely missing the major ingredient: molecular gas (H_2). In fact, nowadays H_2 has almost completely taken the place of HI, which is considered to be mostly irrelevant to the star formation process. Its inclusion solved the problem of Orion's kinematics that had always been problematical as they never could be made to fit expansion, contraction or rotation in a satisfactory manner. For me, they provided the solution to the observed HII region structures, if I could prove that they were all Orion-like. The opportunity came in 1975 when Habing had arranged that I should visit Thaddeus in New York City for a few months. At the same time that Blair, Peters and Vanden Bout (1975) established that Sharpless HII regions more often than not showed CO emission, I used Thaddeus' Columbia millimeter-wave dish and Vanden Bout's larger millimeter dish at McDonald Observatory in Texas to systematically measure the velocity difference between the ionized gas and the associated molecular cloud. The available morphological and kinematical data so obtained convincingly showed that almost all HII regions fit a configuration that we compared to a blister on the human skin: well-defined very bright ionization fronts eating into a very much larger molecular cloud from which gas is streaming away into interstellar space, becoming more and diffuse

with increasing distance (Israel, 1976). Only very large, highly evolved HII regions, often resulting from the merger of overlapping HII zones do not fit this description any more. It is interesting to note that this entire insight was but the last in a chain of steps, and that required the combination of two different techniques: aperture synthesis mapping of centimeter-wave radio continuum mapping and single-dish millimeter wave molecular line measurements.

An important consequence of the blister model was that the exciting stars should have formed inside the molecular clouds, but near the edge and not at the center. Subsequently, the gas dynamics were successfully modelled in Tenorio-Tagle's (1979) Champagne model. This state of affairs seemed so obvious that it did not occur to me that it was not common knowledge in the HII region community. In the summer of 1977, I discovered to my surprise that this was nevertheless the case, when I was participating in a workshop on Giant Molecular Clouds. This led me to turn the relevant but unpublished part of the thesis into a separate paper (Israel, 1978) that is occasionally still being cited. For the first but not the last time, it made me realize that whatever familiarity has made obvious to one can be entirely new to others. I still find it amazing that it took everybody, including myself, so long to discover the importance of molecular gas clouds and the nature of HII regions when it was staring us in the face.

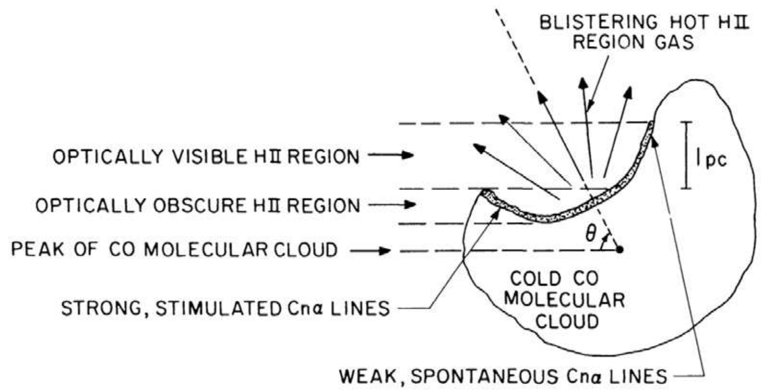

Figure. 4: Schematics of a blister HII region. From Rodney & Reipurth (2008).

7. Slowly, slowly

Missing the obvious kept on occurring. We had no answer to the question why massive stars would preferentially form near molecular cloud edges rather than the center where densities were supposed to be higher. Was star formation always caused by molecular clouds colliding? Observational evidence did not support that. Were molecular clouds perhaps flat and two-dimensional like sheets or pancakes? That did not appear very likely, either. Yet, these suggestions were very close to the solution that once more kept staring us in the face for years. If one looks, for instance, at the very nearby Ophiuchus cloud complex, multiple streamers of gas and dust are immediately obvious. Yet it took the far-infrared maps of the Herschel Space Observatory, launched in 2009, to establish that filaments are ubiquitous, and that molecular clouds are not bulky entities but almost entirely consist of filaments which themselves may consist of tightly wound fibers. Star formation is now thought to take place where filaments interact, and the scales of action approach those where magnetic fields might come into play.

The very one-dimensional structure of filaments makes it unavoidable that stars always form near a cloud edge: there is no other place. It took us over 40 years to see this obvious truth.

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