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ULTRACOMPACT H II REGIONS: NEW CHALLENGES

S. E. Kurtz

Instituto de Astronomía, Universidad Nacional Autónoma de México

RESUMEN

El nombre de "región H II ultracompacta" (UC H II) apareció por primera vez en la literatura hace mas de 30 años. Desde entonces se han identificado del orden de 10^3 regiones o candidatos a UC H II y se han propuesto al menos siete modelos para explicarlas. Las evidencias observacionales recientes indican que la clasificación usual de UC H II puede ser inadecuada para todas las nebulosas densas y pequeñas que rodean a las estrellas masivas jóvenes. En particular, algunas UC H II parecen ser las regiones densas de estructuras más grandes a las que llamamos "UC H II con emisión extendida". Otras regiones H II parecen ser un orden de magnitud más pequeñas y dos órdenes de magnitud más densas que las UC H II tradicionales. Ellas merecen una nueva clasificación y las llamamos "regiones H II super-ultracompactas". Damos un resumen histórico y científico de las UC H II, presentamos los nuevos datos observacionales que dan origen a las nuevas clasificaciones y discutimos brevemente las implicaciones para los modelos teóricos.

ABSTRACT

The designation "ultracompact H II region" first appeared in the astronomical literature over 30 years ago. Since that time, of order 10^3 actual or candidate ultracompact (UC) H II regions have been identified, and no fewer than seven theoretical models have been proposed to describe them. Recent observational evidence suggests that the conventional "UC H II" classification may not be adequate to describe all of the small, dense nebulae surrounding young, massive stars. In particular, it appears that some UC H II regions may be small, high density regions that are integral parts of much larger structures; these we call "UC H II regions with extended emission". Other H II regions appear to be an order of magnitude smaller and two orders of magnitude denser than traditional UC H II regions, and hence are deserving of a new classification. We designate these as "super-ultracompact H II regions", (though we suspect that "hypercompact" will prevail). We provide brief scientific and historical perspectives, present the new observational data and arguments for the new classifications, and briefly discuss possible implications for theoretical models of UC H II regions.

Key Words: **H II REGIONS — STARS: EARLY-TYPE — STARS: FORMATION**

1. SCIENTIFIC PERSPECTIVE

Massive star formation doesn't have a "standard model" yet, in quite the way that low-mass star formation does. The closest we presently come to such a model is merely a scaled-up version of low-mass star formation. This model has roughly four stages. Initially, the molecular cloud is optically thin and undergoes isothermal collapse, characterized by the free-fall time of around 10^5 yr. As densities increase, the gas/dust mixture becomes optically thick and absorbs energy from the protostar, increasing the temperature; evolution is now on the Kelvin-Helmholtz timescale of order 10^4 yr. At some point, presumably, the molecular environment in which the star is forming is sufficiently compressed and heated to produce a hot molecular core, of density $n_{H_2} \gtrsim 10^7$ cm^{-3} and temperature T $\gtrsim$ 100 K. Timescales for the hot molecular core stage are unknown, but 10^3

to 10^4 yr seems plausible (Kurtz et al. 2000). Eventually, when nuclear burning has begun and conditions are such that the ionizing photon flux cannot be contained, an ultracompact (UC) H II region forms. If a UC H II region expands at the sound speed of the ionized gas ($\sim$ 10 km s^{-1}), its lifetime in the ultracompact state should be of order 10^4 yr. Many more UC H II regions are seen than expected in this simple view; the actual lifetime is thought to be of order 10^5 yr. Nominal values for UC H II parameters are sizes less than 0.1 pc, electron densities greater than 10^4 cm^{-3}, emission measures (EM) greater than 10^7 pc cm^{-6} and ionized masses of order 10^{-2} $M_\odot$. At a distance of about 5 Kpc, these regions would be about $4''$ in size. The UC H II phase, both its beginning and its later evolution, is the topic of this presentation.

Not only are many details of the above model unknown, but the very scheme itself is suspect. Stahler, Palla, & Ho (2000) review some of the problems (and possible alternatives) but simply put, the disruptive effects of OB (proto)stars are so great that it is difficult to see how mass accretion by infall can ever build up stars of more than about 10 $M_\odot$. For the moment, we indulge ourselves, and accept this not-quite-standard-model as outlined above. Hence, we provisionally accept that hot molecular cores containing massive protostellar objects exist, and that they are the immediate forerunners of ultracompact H II regions.

2. HISTORICAL PERSPECTIVE

Compact H II regions were first identified and named as such by Mezger et al. (1967), although Ryle & Downes (1967) seem to have used the term slightly earlier. Mezger et al. described compact H II regions as having sizes from 0.06 to 0.4 pc, and electron densities close to 10^4 cm^{-3}. Qualitatively, they described these regions as "small, high-density H II regions *in extended H* II *regions of lower electron density"* (emphasis added). These "extended" regions have sizes of order 10 pc and densities of order 10^2 cm^{-3}. DR21 was one of the original compact H II regions reported, and it is worthwhile to consider how the classification of H II regions evolved as higher resolution data became available. Figure 1 shows a montage of three early observations of DR21. It was first detected (and named) as the brightest source in the 5-GHz continuum survey of Cygnus-X, made by Downes & Rinehart (1966). Interferometric observations (Ryle & Downes 1967) failed to resolve the source, but confirmed it as the highest excitation measure H II region theretofore detected, and earning it the distinction of being the first compact H II region discovered. Still higher resolution observations (Harris 1973) resolved the source, and showed internal structure: higher density components embedded within more diffuse emission. These small, high density clumps came to be called ultracompact H II regions, and at sub-arcsecond resolution they are the only components that appear (Kurtz, Churchwell, & Wood 1994).

In the late 1960s, only a handful of these objects were known, including DR21, K3-50, W3, and W49A. Over the next decade, the number of objects increased steadily, so that the 1979 Annual Reviews article of Habing & Israel listed approximately 60 compact and 40 ultracompact H II regions. Relatively little was known about their internal structure, however. This situation changed dramatically in 1989, with the publication of the Wood & Churchwell catalog of UC H II regions. They identified about 75 regions, and more importantly, they established the lifetime problem and the existence of UC H II region morphologies, both of which have given rise to much theoretical activity. Other surveys of UC H II regions include Garay et al. (1993), Kurtz et al. (1994; hereafter KCW), Miralles, Rodríguez, & Scalise (1994), and the Galactic Plane Surveys summarized by Becker et al. (1994). With some exceptions (notably Becker et al.) these surveys were made at high angular resolution, to determine source structure and morphologies.

Interferometers act as spatial filters: they are sensitive only to a range of angular sizes, roughly corresponding to the ratio of the longest to the shortest baseline length. Any particular baseline in the array (i.e., the spacing between any pair of antennas) is sensitive to an angular size inversely proportional to the baseline length, typically measured in units of the observing wavelength, i.e., $\Theta \sim (B/\lambda)^{-1}$. Hence, large structures are seen by short baselines and small structures are seen by long baselines; so the ratio of the maximum to minimum baseline gives the approximate range of angular sizes that can be seen. For the VLA, where most of the surveys were made, this range is typically a factor of about 40 (to within a factor of 2, depending on details of the imaging). Hence, for resolution $\lesssim 1''$ (i.e., adequate to resolve $4''$ sources) the largest structure that can be imaged by the VLA is about $20''$–$40''$ in size. This was viewed as a "feature not a bug" in several of the aforementioned surveys. If extended emission was present, it was regarded as "contamination": unrelated emission that caused imaging problems for the arcsecond-sized UC H II regions. That high resolution data filtered most of it out was seen as desirable effect.

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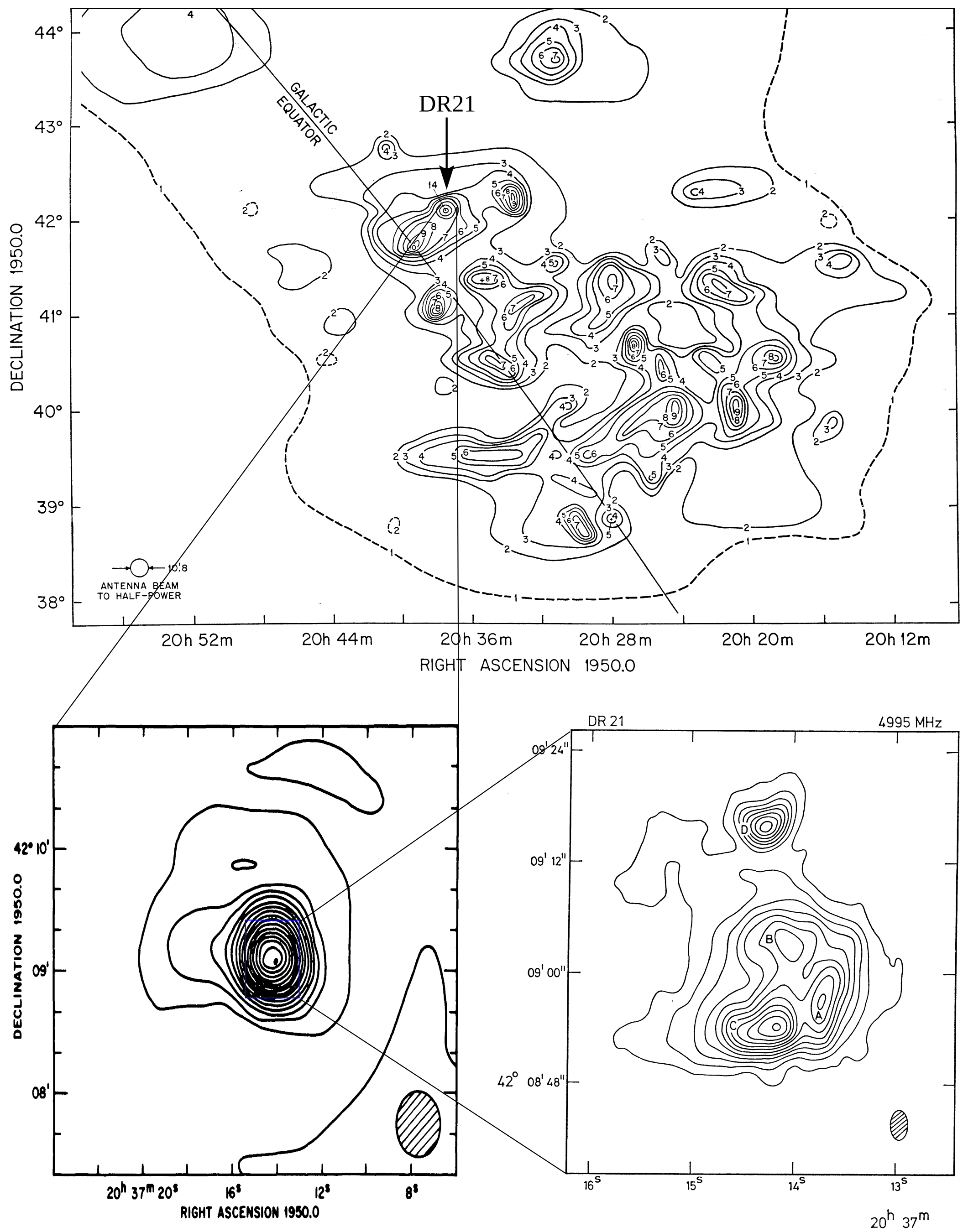

Fig. 1. This sequence of radio images shows the evolving view of (ultra)compact H II regions. *Top,* is the single-dish (10$'\!.$8 beam) 5-GHz image of the Cygnus-X region, made by Downes & Rinehart (1966). The source DR21, indicated by the arrow, was unresolved and was the brightest source detected. *Bottom left,* is the DR21 region, imaged at 1.4 GHz with the Cambridge 1 Mile Array. The source is still unresolved, now with a beam of $34'' \times 23''$. Limits on the size and density lead this region to be classified as "compact." From Ryle & Downes (1967). *Bottom right,* is the same field, imaged with the Cambridge 5 km Array. The resolution is $3'' \times 2''$. At this level, structure within the "compact" H II region begins to emerge. The components A–D are now known as "ultracompact" H II regions. From Harris (1973).

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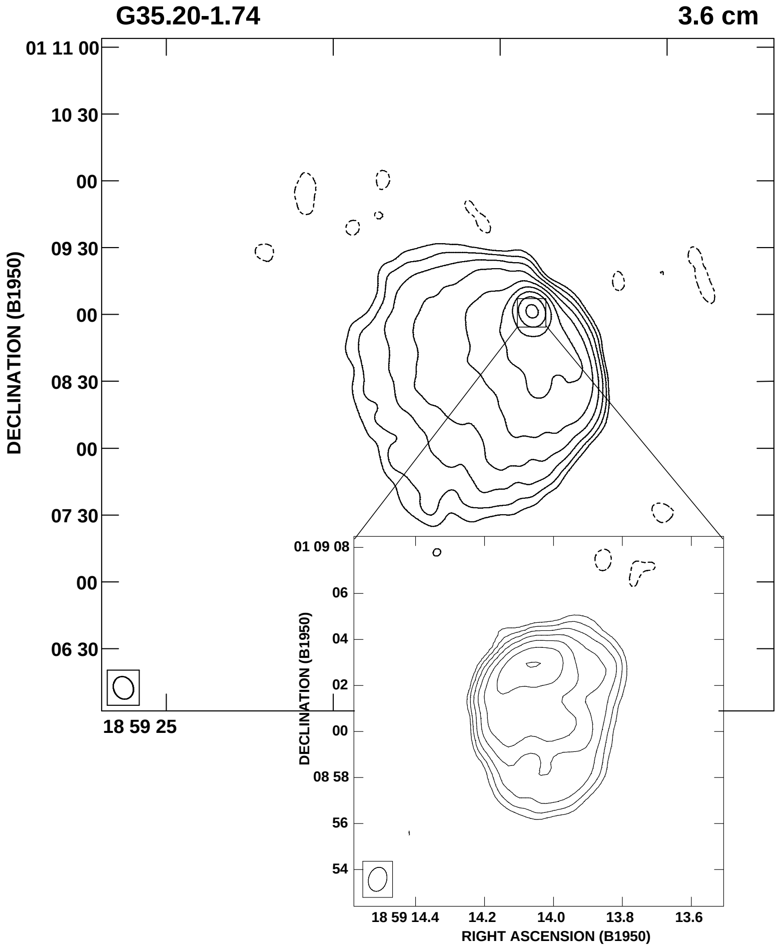

Fig. 2. Two views of the H II region G35.20−1.74. The original view (inset), made with sub-arcsecond resolution, was sensitive only to structures smaller than about 20″ (Wood & Churchwell 1989; Kurtz et al. 1994). Subsequent lower resolution observations, sensitive to structures up to 3′ in size, show the full extent of the ionized gas in the region. The region has a cometary morphology at both arcsecond and arcminute scales.

3. H II REGIONS WITH EXTENDED EMISSION

VLA observing programs are often begun at low angular resolution to determine from the outset if large structures are present. If one begins at high resolution, one is left wondering if perhaps large scale structure is present. This concern, along with several obvious cases that were stumbled upon (see Fig. 2) led several groups to search for extended emission that might be physically related to the ultracompact emission. To date, three such studies have been made. Each had rather different selection criteria, and encountered rather different results; we discuss them in turn.

Ellingsen et al. (2000) used the Australian Compact Array to observe a sample of six UC H II regions. Preliminary results show extended emission in only one of these. Their chief selection criterion was the presence of methanol masers. This criterion may have a significant impact on the incidence of extended emission. If (as Ellingsen et al. suggest) methanol masers trace a relatively early evolutionary state of UC H II regions, then this sample may represent young star formation regions, that have not had time to form an extended, diffuse component. Kim & Koo (2000) made VLA observations of 16 sources, and detected extended emission in *all* cases. They selected sources from the Wood & Churchwell (1989) survey that had significantly higher flux densities in single-dish observations compared to the high resolution VLA observations. Hence, the likelihood of extended emission in these regions was very high. An earlier work by Koo et al. (1996) showed extended emission in G5.48−0.24. Kurtz et al. (1999) randomly selected 15 sources from the KCW survey, and observed them with low angular resolution (and sensitivity to large angular structures) with the VLA. They found extended emission in 12 of the 15 fields, and in eight of these they consider it possible, on morphological grounds, that a direct physical connection exists between the extended and the ultracompact components.

What does all this extended emission mean? Perhaps nothing. From our historical perspective, it's hardly surprising that we see extended emission in some fields: that's how compact and ultracompact H II regions were discovered, as small condensations within a diffuse envelope! Moreover, Panagia, Natta, & Preite-Martinez (1978) showed that clusters of massive stars can give rise to intriguing (but meaningless) morphologies—including UC peaks within an extended envelope—merely by projection effects. The important question to address is whether the extended, low-density component is physically related to the ultracompact component.

One test of the relationship between the ultracompact and the extended components may be the comparison of high quality, centimeter continuum images with near-infrared (NIR) recombination line (e.g., Brγ) images. The idea is to map the extinction toward both components; if both are located within the same general region of the parent molecular cloud then both should have roughly the same extinction. NIR observations also have tremendous potential for determining the stellar content of the UC H II regions, as shown by Watson et al. (1997), Watson & Hanson (1997), and Walsh et al. (1999). Very deeply embedded UC H II regions are not detectable in the NIR, however. And one can easily imagine cloud/H II geometries which would give ambiguous results. Another test might be the mapping of radio recombination lines (RRL) toward these regions. Continuity in the line velocities would be an indicator of physical association between the components. Multi-line data sets would also permit more accurate determination of the densities and temperatures of both components. Detection of RRL from the low surface brightness extended component will be (telescope) time-consuming. But coupled with moderate-excitation molecular tracers such as NH_3 (2,2) or (3,3), RRL may prove a powerful diagnostic.

If extended emission *is* directly connected with the ultracompact component in a significant number of sources, then there may be several important repercussions for UC H II regions. First, the lifetime problem mentioned in § 1 may not be so severe as previously thought. If a significant fraction of "ultracompact" H II regions are actually much larger, it would mitigate the lifetime problem. Second, conclusions regarding the energetics and absorption of UV photons by dust will also be affected. Centimeter continuum emission reflects the total *ionizing* flux from the exciting star(s), while the far-infrared (FIR) emission reflects the total *energy* flux from the star(s). Circumstellar dust and clusters of stars are almost certainly present, and both will affect the relative contribution of centimeter and FIR flux. The flux density of the extended emission is frequently equal to that of the UC component, which will significantly affect the analysis of the cm/FIR contributions. Among other things, this suggests that the absorption of UV photons by dust (KCW, WC) has been over-estimated.

At least six theoretical models have been proposed for UC H II regions, and in retrospect, they fall into two classes: those that attempt to resolve the lifetime problem by *confining* the ionized gas, and those that *replenish* the ionized gas. In the former category are ram pressure of in-falling matter (Wood & Churchwell 1989), stellar wind bowshocks (van Buren et al. 1990), high ambient pressures (De Pree, Rodríguez, & Goss 1995; Akeson & Carlstrom 1996; García-Segura & Franco 1996; Xie et al. 1996). In the latter category are champagne flows (Tenorio-Tagle 1979), photoevaporating disks (Yorke & Welz 1996; Hollenbach et al. 1994), and mass-loaded flows (Dyson, Williams, & Redman 1995; Lizano et al. 1996).

It is not yet clear what ramifications extended emission might have for these models. We can make a few preliminary comments, however. First, we note that the challenge is probably still to confine or replenish the ultracompact gas. If an extended envelope is present, it is likely to expand following a more traditional mechanism (see García-Segura & Franco 1996; Franco, Tenorio-Tagle, & Bodenheimer 1989, 1990). Second, it appears unlikely that some models can scale up sufficiently to explain the larger regions. The bow-shock model, for example, is unlikely to explain cometary regions on a scale of $2'$, such as G35.20−1.74 (Fig. 2). High thermal pressures (from 10^7 cm^{-3}, 100 K molecular gas) are clearly not present on scales of tens of parsecs. Nor are they needed, since the extended component is of much lower pressure, and presumably is not confined. Finally, we note that current replenishment models probably cannot account for the extended envelopes. The mass of the extended components so far detected is of order 100 $M_\odot$—much greater than the mass which would likely be present in circumstellar disks or clumps within the star-forming core. Either some way of processing

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much more core mass must be found, or we will likely conclude that the extended gas was ionized *in situ*, not ejected from the UC region at some earlier time.

4. SUPER ULTRACOMPACT H II REGIONS

We turn now to the second challenge, occurring at the opposite size extreme, namely super ultracompact H II regions. I will use this term to mean H II regions with sizes of order 0.01 pc or smaller and densities of 10^6 cm^{-3} or greater, implying emission measures of order 10^{10} pc cm^{-6} or higher. We claim below that this is a newly discovered class of object. We refer to these objects as "super ultracompact H II regions", but it seems likely that they will ultimately be known as "hypercompact H II regions."

An important result in recent studies of massive star formation sites is the presence of warm, high density molecular gas (see Kurtz et al. 2000 and references therein). These hot molecular cores, described in § 1, are thought to be the immediate precursors of UC H II regions. The mechanism(s) that end the hot core phase and allow the development of a UC H II region are not understood. But presumably, if the hot core gas, of density $\sim 10^7$ cm^{-3}, is suddenly ionized, it will produce an H II region of electron density $\sim 2 \times 10^7$ cm^{-3} and emission measures of order 10^{10}–10^{12} pc cm^{-6}.

This is not only plausible, but seems an inescapable implication of the De Pree et al. (1995) thermal pressure confinement model. They pointed out that the lifetime problem was based on assumptions of molecular core densities of 10^5 cm^{-3} and temperatures of $\sim$ 25 K, as indicated by molecular line data in the late 1980's. More recent data suggest values of 10^7 cm^{-3} and 100 K, and hence a factor of 400 increase in the thermal pressure confining a nascent UC H II region. Xie et al. (1996) noted that such high density molecular cores, when ionized, would produce very high EM objects, of order 10^{10} pc cm^{-6}. Because there was no observational evidence for such high EM objects, they sought an alternative source for the high ambient pressures. They suggested turbulent pressure, thus avoiding the need for high densities and hence high EM.

Massive star formation sites that do not show any centimeter continuum emission are good candidates for "young" stellar objects, either hot cores or SUCH II regions. The water maser survey of Hofner & Churchwell (1996) presented a number of possible candidates. They observed 21 UC H II regions and found a striking correlation of maser position with UC H II morphology: for cometary regions, the masers virtually *always* lie in one or more distinct clumps, slightly offset from the cometary arc. For the other morphologies there is no apparent pattern in the maser positions. If these maser clumps are massive star formation sites, then millimeter continuum emission from ionized gas or warm dust may be detectable. Carral et al. (1997) made 7 mm observations to search for such emission; their results for G75.78+0.34 (aka ON-2), are shown in Figure 3. On the left is the original UC H II region map by Wood & Churchwell (1989); the crosses indicate the water maser positions. Six cm continuum emission is notably absent at the maser clump position. At 7 mm, however, substantial continuum emission is seen. Subsequent VLA and OVRO observations provided flux densities from 3.6 cm through 1 mm, with a nearly constant spectral index of $\alpha = +1.7$ throughout this range. At a distance of 4.7 Kpc, the size appears to be $\lesssim 0.005$ pc, and its emission measure is $\gtrsim 2\times10^{10}$ pc cm^{-6}, implying an electron density $\gtrsim 2\times10^6$ cm^{-3}, (assuming the 1 mm emission is primarily thermal bremsstrahlung). To our knowledge, this is the highest emission measure ever reported for an H II region. We note that the electron density is in reasonable agreement with the expected molecular densities for a hot molecular core. It would appear that the very high EM objects implied by thermal pressure confinement have been found.

The G75.78+0.34 maser clump is not the only high emission measure object which has been reported. De Pree, Goss, & Gaume (1998) report 19 UC H II regions in the Sgr B2 Main complex with an average size of 29 mpc, density of 7.1×10^7 cm^{-3}, and emission measure of 2.8×10^9 pc cm^{-6}. These regions are clearly excellent candidates for SUCH II regions which have recently formed within hot molecular cores. Searches for residual molecular clumps surrounding these regions would be very worthwhile, though not easy to carry out at the distance of Sgr B2.

Extremely small (though not high EM) objects have also been reported. Gómez, Rodríguez, & Garay (2000) detected a cluster of six very small ($\sim$ 0.2 mpc) sources near the GGD 14 star-forming region. Supposing these sources to be very young UC H II regions, they estimate spectral types of B2–B3 for the exciting stars, and infer electron densities greater than 10^5 cm^{-6}. Although these EMs are not so high as those mentioned above, it is plausible that these objects are a lower-mass version of SUCH II regions. "Hypercompact H II regions" were reported in W3 by Tieftrunk et al. (1997), where the definition of hypercompact seems to be "smaller

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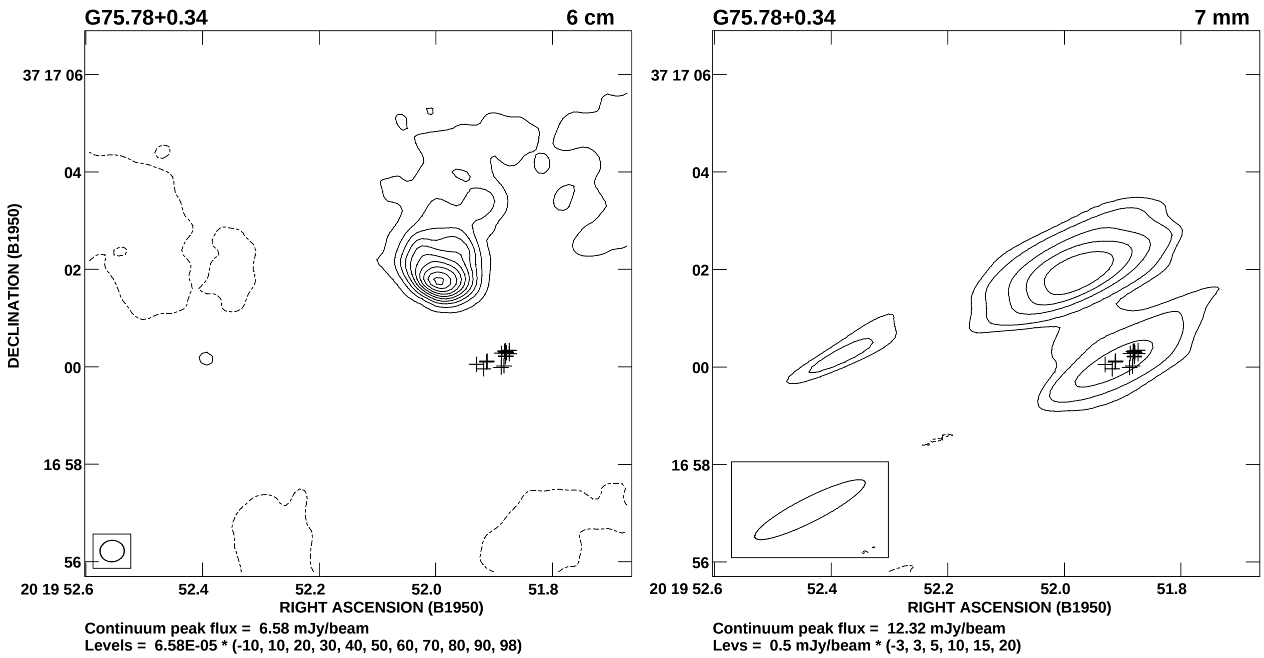

Fig. 3. Two views of the H II region G75.78+0.34. (*Left*) The original view, a 6 cm continuum snapshot made with the VLA (Wood & Churchwell 1989). The crosses indicate water maser positions, detected by Hofner & Churchwell (1996). No centimeter continuum emission was seen coincident with the maser clump. (*Right*) The same field, observed at 7 mm using the VLA (Carral et al. 1997). Millimeter wave continuum emission coincident with the maser clump is clearly present.

than 5 mpc." Some of the sources they detect appear to have EMs as high as 10^8 pc cm^{-6}. Tieftrunk et al. suggest that these hypercompact objects may form a type of "radio zoo" (i.e., various *types* of objects) as seen in Orion (Felli et al. 1993). The sources detected by both Gómez et al. (2000) and Tieftrunk et al. (1997) are intriguing and may hold important information for furthering the massive star formation model. At present, however, we prefer to reserve the terms "super" or "hyper" compact H II regions for regions that are not only small but also have very high densities.

Although only 20 such high EM regions are presently known (and all but one of these are in the Sgr B2 complex), we note that most existing UC H II region surveys might well have missed these objects. The optical depth of free-free emission is

$$\tau = 0.082\, T^{-1.35}\, \nu^{-2.1}\, EM,$$

so regions with EM $\sim 10^{10}$ pc cm^{-6} would remain optically thick into the millimeter regime. Because $S_\nu \propto \nu^2$ for optically thick free-free emission, their centimeter flux densities would be quite low—below the detection limit of some VLA snapshot surveys. A millimeter wave survey might detect a significant number of them.

When *compact* H II regions were defined as a new class of object, they were about a factor of 10 smaller and a factor of 10 denser than the previously known *classical* H II regions. When *ultracompact* H II regions were defined, they were about a factor of 5 smaller and a factor of 5 or 10 denser than *compact* H II regions. We now find objects 10 times smaller and 100 times denser than ultracompact H II regions, so it seems reasonable to claim that they constitute a new class of object, and we accordingly name them SUCH II or hypercompact H II regions. The existence of such very high EM objects lends credence to the thermal pressure confinement model, and they may be the closest we have yet come to observing the transition from a hot molecular core to an H II region.

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S. E. Kurtz: Instituto de Astronomía, UNAM, Campus Morelia, Apartado Postal 3-72, C. P. 58089 Xangari, Morelia, Michoacán, México (kurtz@astrosmo.unam.mx).