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Edge Cloud Conclusions

13.1 Edge Cloud 2

In order to deduce its physical and chemical properties, I have observed continuum emission and a large number of molecular transitions in EC2 at the Galactic edge. I have also made CO maps of EC2 and used these to calculate deconvolved line intensities. A temperature of 20 K was estimated from hyperfine detections of ammonia, and a gas density of $n(H_2) \sim 10^4\,\mathrm{cm^{-3}}$ was determined by comparing LVG models of a number of species to their deconvolved line detections. Molecular abundances were also determined from the LVG models and found to be in good agreement with abundances calculated directly from the deconvolved line intensities. From the peak continuum emission I calculated a dust mass for EC2 and a dust to gas ratio ≥ 0.001.

Through the use of chemical models I have been able to establish the most likely chemical and physical properties of EC2 (although I note that not all observed abundances can be reproduced in a self-consistent manner). There is an indication that heavy elements may be depleted by about a factor of five relative to local molecular clouds (similar to those in dwarf irregular galaxies and damped Lyman alpha systems). Very low extinction ($A_V < 1$ mag) is required for initial abundances above 20 per cent. Such reduced abundances may be related to the low level of star formation in this region and are probably the result of infall of halo gas enriched in O, C and S from a burst of massive star formation in the Galactic halo shortly after the Milky Way was formed. The models also suggest a high UV photon field in EC2 (10–20 × local values), where an increased UV field allows for values of A_V up to 4 mag, especially if this is combined with an increase in CRI (10–20 ×), although the models are less sensitive to increases in the CRI rate. High CRI rates (>20 × the ISM value) without an increase in UV field only allow for extinction up to 2 mag. Gas densities much above $n(H_2) = 1.2 \times 10^4\,\mathrm{cm}^{-3}$ are excluded by the models, even if the UV field is increased. Some of my models indicate that steady-state is reached very quickly after around 5,000 years, and that a high UV field can reduce this to just ∼500 yr, which appears implausible. However, for a very high UV photon field (40 ×) and an extinction of A_V = 3 mag, steady-state is not reached until a more realistic 10^4 yr.

In the context of ratios relative to HCO^+, sulphur-bearing molecules appear to be very over-abundant, and there is also some, albeit weak, evidence that the D/H ratio may be a factor of two less than local values. The observed high abundances (again relative to HCO^+) of the radicals C_2H and CN are typical of photon-dominated regions (PDRs), but at large Galactocentric radii, metal abundances relative to hydrogen are expected to be much reduced. In addition, although EC2 does contain young stars, there is no evidence of the late-type stars which produce dust grains, thereby justifying the assumption of a high ratio of UV flux to grain surface area. I conclude therefore, that despite the position of EC2 in the Galaxy, UV photons (rather than cosmic rays) play an important role in establishing its detailed chemical composition. Also, the observed clumpy structure leads to a much greater surface area, not only for CO self-shielding, but also as an interface between PDR regions.

SNR - a smoking gun for EC2?

Given that EC2 is in a region of extremely low gas pressure and very small spiral arm perturbation, the question remains as to the origin of the structure and chemistry in

EC2. In such low temperature environments the primary pathway for the formation of molecules is gas-phase ion-molecule reactions that do not have activation energy barriers. However, the passage of shock waves through a cloud can produce high temperatures, allowing endothermic reactions that alter the molecular abundances produced by low temperature reactions. As an example, Ziurys et al. (1989) find some evidence, particularly an increase in SiO, for shock chemistry in molecular clouds associated with supernova remnant (SNR) IC 443. Turner et al. (1992) also examine the shock chemistry related to IC 443 and conclude that nondissociating (ND) and dissociating (D) shock models seem to to explain the observed abundances in the cloud IC 443G.

More recent work by Stil and Irwin (2001) speculates that old SN shells may be a source of dense clouds in low density environments such as the outer Galaxy. They go on to show that GSH 138–01–94 is the largest and oldest SNR known to exist in the Milky Way. It consists of a H I shell at a kinematic distance 16.6 kpc, with an expansion velocity of 11.8±0.9 km s^{-1}, an expansion age of 4.3 Myr and a timescale for dissolving into the ISM of 18 Myr. They show that GSH 138–01–94 can live longer, because of the lower density in the outer Galaxy, and because an expanding shell in this region can grow five times larger before bursting out of the Galactic disk. Their observations also agree with hydrodynamic models for a SNR in a low density, low metallicity environment such as the Galactic edge, and provide direct evidence for the release of mechanical energy into the outer Galaxy ISM, where the kinetic energy of the expanding shell is 3×10^{43} J, consistent with 10^{44} J released in a single supernova explosion. Most interestingly, Stil and Irwin associate EC2 with the approaching side of the H I shell (reducing the distance of EC2 to 16.6 kpc, in close agreement with the photometric distance of the B star MR1). Fig. 13.1 shows the H II region in GSH 138–01–94 located on the southeast edge of Cavity 1 where GSH 138–01–94 also appears to make contact with EC2.

I therefore make the tentative conclusion that the formation, structure and hence chemistry of EC2 is as a direct result of shock fronts from GSH 138–01–94 propagating through EC2 sometime between 1,000 and 10,000 years ago, as this would explain

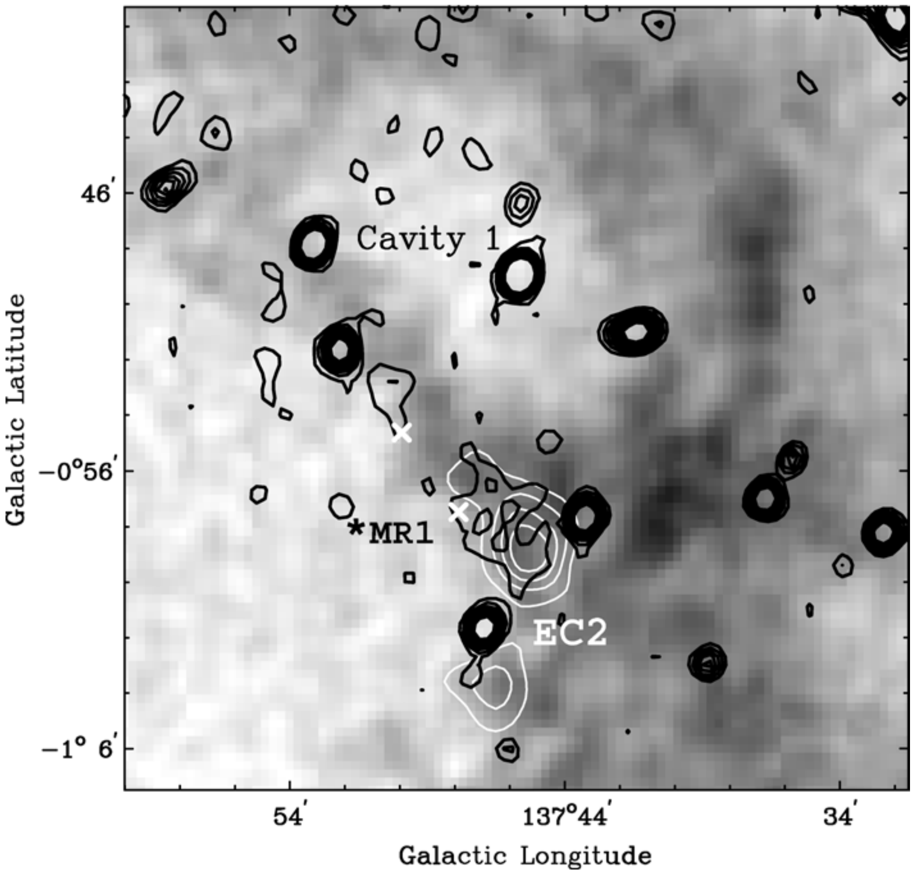

Figure 13.1: Detail of SN remnant GSH 138–01–94 (Stil and Irwin 2001, fig. 5) displaying the area around cavity 1. Gray scales represent H I and white contours give the CO brightness of EC2 from Digel et al. (1994). 21 cm continuum is shown as black contours. The * sign indicates the position of MR1, and peaks in Hα emission are indicated by a cross.

my observation of gas in EC2 at a steady-state early time of $< 10^4$ yr. EC2 could even have been formed by GSH 138–01–94 from swept-up interstellar gas, through Rayleigh-Taylor instabilities, and therefore be as young as discussed above. Supernovae are also producers of cosmic ray particles, so GSH 138–01–94 may be the source of the enhanced levels of CRI suggested by my models. Although the line widths in EC2 ($\sim 2\,\mathrm{km\,s^{-1}}$) are considerably less than the SNR expansion velocity, it can be argued that, because of mass conservation, the SN shell would have moved more slowly through the denser material of EC2. Also, the age of the hot blue-white star MR1

($M = 22\,M_\odot$), associated with EC2, which is just evolving off the main sequence (Smartt et al. 1996), is of the order of 10 Myr, which is consistent with the expansion age of GSH 138–01–94, and the detected NIR sources in EC2 (Kobayashi and Tokunaga 2000) are suggestive of progressive star formation a long time after the single SN trigger event.

Summary of EC2 properties

Temperature $T = 20\,\mathrm{K}$.

Density $n(\mathrm{H_2}) \sim 10^4\,\mathrm{cm^{-3}}$.

Cosmic Ray Ionisation CRI = 10–20 × $1.3 \times 10^{-17}\,\mathrm{s^{-1}}$.

UV photon field UV = 10–20 × local ISM values.

Initial Abundance IA = 20 per cent of local ISM values.

Extinction $A_\mathrm{V} < 4\,\mathrm{mag}$.

Dust to gas ratio $M_\mathrm{dust}/M_\mathrm{gas} = 0.001$–$0.015$.

Mass $M_\mathrm{EC2} \approx 10^4\,M_\odot$.

13.2 Edge Cloud 1

My investigations of EC1 are to date less extensive compared to EC2, but EC1 appears to be chemically less interesting. This is not surprising, as it does not appear to have the benefit of an associated H II region excited by an early B star, to stimulate a more dynamic chemistry. The apparent molecule-poor nature of EC1 may demonstrate the characteristics of gas clouds that have not had the benefit of SN shocks to stimulate an active cloud chemistry.

13.3 Further edge cloud work

As stated in the introduction to Part II, Galactic edge clouds are comparable in size and mass to local molecular clouds, and as has been established in the foregoing, EC2, in particular, is worthy of further research, as it presents the opportunity to investigate the properties of star formation in low metallicity molecular environments. Therefore I envision the following further edge cloud work: Compare results (both elemental and molecular abundances) with those in other dwarf galaxies, particularly the Magellanic Clouds (e.g. see Chin et al. 1996, 1997, 1998), or with studies of star formation in very low metallicity environments such as molecular clouds in the Magellanic Bridge (e.g. see Mizuno et al. 2006). Better define cloud properties by refining the chemical kinetic model, including initial abundances and reaction rates, to better match observed molecular abundances. Determine how the CO/H_2 ratio at the Galactic edge varies with metallicity and environment. Mapping EC1 and EC2 in ^{12}CO, ^{13}CO and $C^{18}O$ (1–0) at 3mm using the ARO 12m or Onsala 20m telescopes. Mapping EC1 in ^{12}CO, ^{13}CO and $C^{18}O$ (2–1) and (3–2) at 1.5 and 1mm using the JCMT 15m telescope. Complete higher sensitivity dust continuum maps of EC1 and EC2 at 1200 microns using the IRAM 30m telescope and bolometer. Further observations of EC1 to compare with EC2 to confirm existence (or not) of gradient at large Galactocentric distances for low metallicity gas using: the Arizona Radio Observatory 12m telescope at 3–2mm; the MPIfR Effelsberg 100m telescope at 1.2, 2 and 6cm; and the Onsala Space Observatory 20m telescope at 3mm. Improved IR maps using for example the Spitzer Space Telescope (SST) for imaging at 4–160 microns and spectroscopy at 5–40 microns. PDR modelling to confirm whether or not EC2 is such a region. Investigate the NIR sources in EC2 with the SST and their relationship (or not) with the cloud. Seek to establish the role of MR1 in triggering star formation in EC2, and the relationship between EC2 and the nearby H II region.