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Evidence for selective photodissociation of CO and an enhanced C/O elemental ratio in the gas phase in NGC 253

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In the central ~300pc of the circum-nuclear region of the starburst galaxy NGC 253 the bulk of the molecular gas is hot (T~100K) and dense (n> 10^4 cm^{-3}) and the chemistry of this gas is dominated by the large UV field from newly born massive stars. Furthermore, towards NGC 253:

- standard models of UV photon dominated chemistry can only account for <5% of the observed [CI] emission.
- there is a high C/O elemental ratio in the gas phase.
- $C^{18}O$ is a poor tracer of the bulk of the molecular gas.
- selective photodissociation of CO and its isotopomers is efficient.

INTRODUCTION

Nearby (~ 2.5 Mpc; de Vaucouleurs 1978) and luminous at all wavelengths, NGC 253 is a very dusty, highly inclined spiral which, along with M82, has become an archetypal starburst galaxy. High-resolution millimetre-wave observations show that a 40″x10″ FWHM barlike feature dominates the ^{12}CO J=1 → 0 emission (Canzian *et al.*1988). The existence of a starburst in NGC 253 is supported by the high far-infrared luminosity L_{FIR}=1.6x10^{10} $L_\odot$, most of which originates within the central 30″ (Telesco & Harper 1980), IR hydrogen recombination Brackett line fluxes (Beck & Beckwith 1984), and ionic and atomic fine structure lines (Carrall *et al.*1994).

Isotopic CO in NGC 253

Wall *et al.*(1991) observed the integrated temperature ratio of ^{13}CO 3→2/2→1 to be ~2.0 in the central 23″ (~300pc) of NGC 253. Given the uncertainties in the observations (the data were taken from different telescopes) this ratio is close enough to the limiting value of 2.25 to indicate that most, if not all, ^{13}CO emitting gas is hot (T~100K), optically thin and thermalised. Modification due to a subthermal

population of ^{13}CO, an increased optical depth, or a cold component must be small because otherwise the observed 3→2/2→1 temperature ratio of ^{13}CO would be much closer to unity.

C^{18}O paints a different picture of CO excitation towards the nucleus of NGC 253. Over the same region as covered by the observations of Wall *et al.*(1991) we find that the temperature ratio of C^{18}O 3→2/2→1 is ∼1.1, clearly different from ^{13}CO. C^{18}O is optically thin given that ^{13}CO is optically thin. Furthermore, the critical density of the energy levels of ^{13}CO and C^{18}O are close enough that if ^{13}CO is thermalised, C^{18}O will also be thermalised. Hence, it would seem from the 3→2/2→1 ratio that the bulk of C^{18}O emitting gas is cold (T∼20K).

It appears that C^{18}O and ^{13}CO may be tracing different components of the ISM towards the nucleus of NGC 253. Towards the edges of Galactic molecular clouds the effects of selective photodissociation of isotopic CO has been modelled by several groups, *e.g.*Van Dishoeck & Black 1988, who find that ^{12}CO and ^{13}CO become self-shielding to an external UV field at smaller depths into a cloud than does C^{18}O. This results in the column density ratio of ^{13}CO/C^{18}O being enhanced towards the edge of the cloud. It is to be expected that the temperature of the gas will be higher towards the edge of the cloud where UV heating is more efficient. Averaging over an optically thin cloud, such a process would give ^{13}CO 3→2/2→1 > C^{18}O 3→2/2→1, which we have observed in NGC 253. This indicates that UV photons dominate the chemistry of molecular gas in the starburst. The UV photons will also dominate the heating of the molecular gas in NGC 253 and the fact that virtually all ^{13}CO is hot indicates that the bulk of molecular gas in NGC 253 must be at low A_v.

Standard models of UV dominated chemistry can only account for ∼5% of the [CI] emission in NGC 253

Atomic carbon has been observed in Galactic molecular clouds to arise primarily in the transition zone between ionised and molecular gas, Keene (1990). Such zones have been termed Photon Dominated Regions (PDRs) because the chemistry of such regions is dominated by the presence of UV photons. Theoretical models of PDRs have been constructed by several groups, *e.g.*Hollenbach *et al.*(1991). The models of Hollenbach *et al.*(1991) indicate that atomic carbon is quite a robust diagnostic of PDR gas since the [CI] intensity is fairly insensitive to both the density of the gas, n_0, and the impinging UV field, G_0 (G_0 is the factor by which the UV field in the region is larger than the local value).

Carral *et al.*1994 modelled the nucleus of NGC 253 in terms of a population of n_0=10^4 cm^{-3}, G_0=10^4 PDRs with an area filling factor of order unity. The intensity of [CI] in such a PDR is predicted by Hollenbach *et al.*1991 to be ∼ 2×10^{-6} erg cm^{-2} s^{-1} sr^{-1} (see Fig. 2). However, we find from the central 23″ $< I_{CI} >\sim 4\times10^{-5}$ erg cm^{-2} s^{-1} sr^{-1}, a factor ∼20 greater than predicted.

It is possible to make [CI]/[CII] and [OI]/[CII] consistent with a PDR origin for [CI] in two ways, either by reducing the density of the PDR gas to n∼10^2 cm^{-3} or by lowering the UV field. Both ways result in much less [OI] and [CII] being

produced but have little effect on the [CI]. [OI] drops off much more dramatically than the [CII] but shocks result in [OI]/[CII]>1 (Hollenbach & McKee 1989) and so by having an ensemble of PDRs and shocks, with large filling factors, ~20, we can make I[CII]/I[CI] and I[OI]/I[CII] consistent with observations and the PDR models of Hollenbach *et al.*(1991). Unfortunately, both ways result in conflicts with other observations.

Reducing the UV field results in large pressure differentials between different components of the ISM (the different components of the ISM in NGC 253 are close to pressure equilibrium, Carral *et al.*1994) and too much CO (1→0) emission (see Fig. 2). The far-IR luminosity of NGC 253, which arises from hot dust heated by UV photons, indicates that $G_0 \sim 10^4$. Furthermore, the Lyman continuum photon flux from the central 15″ of NGC 253 is $\sim 2\times10^{53} s^{-1}$ (Beck & Beckwith 1984) and given that the effective temperature of the ionising stars is ~35,000K in the nuclear region of NGC 253 (Carral *et al.*1994) G_0 must be of order 10^4.

Given that the temperature of PDR gas is ~300K, reducing the density of the PDRs (to $n\sim10^2 cm^{-3}$) results in large pressure differentials between different components of the gas. Even if we abandoned the assumption that the ISM in NGC 253 is in pressure equilibrium, such low density PDRs would produce far more atomic hydrogen than was observed by Combes *et al.*(1977). Furthemore, given that the J=3 level of ^{13}CO is thermalised highlights that the molecular, and thus PDR, gas must be at densities $>3\times10^4$ cm^{-3}.

It is only at low densities or at low UV fields that I[OI] and I[CII] are low enough to make the O^o, C^+ and C^o consistent with each other. Hence, intermediate densities and UV fields are also ruled out. The [CI] emission we have detected is inconsistent with the picture presented by Carral *et al.*and the models of Hollenbach *et al.*and so we have to look for a non-standard PDR origin for the [CI] emission in NGC 253.

If standard PDR's cannot account for the bright [CI] emission then there must be a high C/O elemental ratio in the gas phase of NGC 253

Recent chemical models (*e.g.*Flower *et al.*1994) suggest that an enhanced ionisation fraction deep within molecular clouds drives the chemistry to equilibrium with a high atomic carbon abundance. To explain the enhanced [CI] emission in M82, with respect to both PDRs and CO, Schilke *et al.*(1993) proposed the enhanced cosmic ray flux supplied by frequently occurring SN remnants in M82 as the source of ionisation. Such a source of carbon emission would seem an attractive solution to the problem of bright [CI] emission from the nucleus of NGC 253. The cosmic ray rates are presumed similar in NGC 253 and M82: since the IR luminosities of the two galaxies are similar, if they have similar IMFs, the star formation, and hence supernova, rates will be comparable. We believe, however, that the state of the bulk of molecular gas in NGC 253 rules out the Flower *et al.*model as a possible solution.

The bulk of molecular gas in NGC 253 is at low A_v, hot and exposed to UV photons. In such an environment, the chemistry will be photon dominated, and the small perturbation of an extra ionising source such as cosmic rays should have little

bearing on the chemical abundances. The cosmic ray explanation also requires atomic carbon emission to steadily rise with depth into the cloud. In NGC 253, this rise with depth is curtailed at a few A_v. Thus, there is not enough cold and shielded gas for a contribution to the [CI] emission to be significant.

Time-dependent chemical models reach equilibrium abundances after about 10^7 yrs, Keene (1990). These models show that at early times, *i.e.*$<10^6$ yrs, there is large abundance of C^o and the C^o/CO ratio is greater than at late times when equilibrium is reached. It is very hard to distinguish observationally between early-time chemistry and a high C/O elemental ratio as both models produce similar chemical abundances, e.g. molecules that are carbon-rich. However, in order for the C^o/CO ratio in NGC 253 to be explained by early time chemistry we must be seeing a snapshot of NGC 253 when a major reconfiguration of the interstellar medium has occurred within $\sim 10^6$ yrs across a region of size $\sim$ 300pc. We feel that this is implausible. Furthermore, the chemistry in NGC 253 is dominated by UV photons, which produces very different chemical abundances than the chemistry of cold, dark clouds. The environment of the bulk of molecular gas in NGC 253 indicates that time dependent chemical models may not be applicable in the starburst region.

Since the chemistry in NGC 253 is photon dominated, the only plausible explanation of our observation of [CI] in NGC 253 is to invoke an enhanced C/O elemental ratio in the gas phase of the starburst region.

References

Beck, S.C. & Beckwith, S.V. 1984,MNRAS,207,671

Canzian, B. , Mundy,L.G. & Scoville,N.Z. 1988,ApJ,333,157

Carral, P. ,Hollenbach, D.J. ,Lord, S.D. ,Colgan, S.W.J ,Haas, M.R. ,Rubin, R.H. & Erickson,E.F. 1994, ApJ, 423, 223

Combes, F., Gottesman, S.T. & Weliachew,L. 1977, A&A, 59,181

de Vaucouleurs, G. 1978, ApJ,224,79

Flower, D.R. ,Le Bourlot, J. ,Pineau des Forêt.s, G. & Roueff, E. 1994,A&A,282,225

Hollenbach, D.J. & McKee, C.F. 1989,ApJ,342,306

Hollenbach, D.J. ,Takahashi, T. & Tielens, A.G.G.M. 1991,ApJ,377,192

Keene, J. 1990 in Carbon in the Galaxy: studies from earth & space, ed. Tarter, J.C. , Chang, S. & Defrees, D.J. (NASA CP-3061),181

Schilke, P. ,Carlstrom, J.E. ,Keene, J. and Philips, T.G. 1993,ApJ,417,L67

Telesco, C.M. & Harper, D.A. 1980,ApJ,235,392

Van Dishoeck, E.F. & Black, J.H. 1988,ApJ,334,771

Wall, W.F. ,Jaffe, D.T. ,Israel, F.P. & Bash, F.N. 1991,ApJ,380,384