Astrochemistry: Recent Successes and Current Challenges
Proceedings IAU Symposium No. 231, 2005
D.C. Lis, G.A. Blake & E. Herbst, eds.

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doi:10.1017/S1743921306007253

Chemistry in the Dense Molecular Gas of Starburst Galaxies and AGNs

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Abstract. Understanding the molecular phase of the ISM in starburst and active galaxies is important for the modelling of the onset and evolution of their nuclear activity. Observations of high density gas tracers such as HCN, HNC, HC_3N, HCO^+ and CN are essential for probing physical and chemical conditions of the dense, star-forming gas. These tracers show great potential as indicators of the evolution of star formation as well as probes of X-ray illuminated molecular gas around an active galactic nucleus (AGN). In particular, towards the inner kpc of luminous and ultra luminous galaxies will molecular line ratios prove useful as diagnostic tools, since optical and even near infrared starburst tracers are difficult to apply in these highly obscured regions.

Keywords. astrochemistry — galaxies: active — galaxies: evolution — galaxies: ISM — galaxies: starburst — ISM: abundances — radio lines: galaxies — radio lines: ISM

1. Introduction

In order to understand the activities in the centers of luminous galaxies it is essential to also study the physical conditions of the dense gas component. The lower transitions of ^{12}CO and ^{13}CO typically trace gas in the density range $n(H_2) = 10^2 - 10^3$ cm^{-3} while the polar molecule HCN is commonly used as a tracer of dense molecular gas, i.e. gas at $n(H_2) \geqslant 10^4\,\mathrm{cm}^{-3}$ (e.g., Solomon *et al.* 1992; Helfer & Blitz 1993; Paglione *et al.* 1995; Curran *et al.* 2000; Gao & Solomon 2004). Solomon *et al.* (1992) and Gao & Solomon (2004) find a tighter correlation between FIR and HCN luminosity than the one previously found between FIR and CO. They suggest that, in general, the IR luminosities originate from star formation rather than AGN activity in FIR luminous galaxies.

However, in order to understand both the nature and evolutionary stage of the processes involving the dense gas phase it is essential to both study the excitation of HCN as well as the relative intensities and excitation of other high density gas tracers. In this review I will briefly discuss CN, HNC, HC_3N and HCO^+ and their interpretation in terms of central activity. In general, it is found that galaxies with otherwise similar FIR/HCN, or CO/HCN, luminosity ratios may show vast differences in the properties and chemistry of their dense gas.

This paper is focussed around some aspects of chemistry of the dense gas in luminous ($L_{\mathrm{IR}} > 10^{11}$ L$_\odot$, LIRGs) and ultraluminous ($L_{\mathrm{IR}} > 10^{12}$ L$_\odot$, ULIRGs) galaxies. Significant advances have been made lately in the high-resolution study of chemistry in less luminous, nearby galaxies—for example of the starburst region in the nucleus of IC 342 (e.g., Meier and Turner 2005); NGC 253 (e.g., Martin *et al.*) and in the active nucleus of NGC 1068 (e.g., Usero *et al.* 2004).

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2. Molecular Line Ratios as Diagnostic Tools

The starburst and AGN activities of many luminous IR galaxies are obscured by large columns of dust, aggravating – and sometimes prohibiting – the studies of the properties of the activity though optical, UV, and even NIR diagnostic methods. For example, Gonzáles-Alfonso *et al.* (2004) suggest an extremely high extinction of $A_V \approx 10^4$ towards the nuclei of the ultraluminous merger Arp 220. Spectral lines and continuum at longer wavelengths are therefore useful additional diagnostic tools to determine properties and evolution of the central activity of luminous galaxies, for example radio continuum and radio recombination lines (e.g., Yun *et al.* 2005).

The properties of the star-forming gas can also be studied via its chemistry and here we will briefly discuss a few line ratios for the dense gas, mainly HCO^+/HCN, HNC/HCN and CN/HCN. It is important to note that the regions studied are compact, and are often only marginally resolved even by mm-wave interferometers, such as the OVRO or Plateau de Bure arrays. Therefore, the properties of the gas traced by the measured line ratios are the *average* properties of the gas within the beam. When ALMA comes on line, this will change dramatically since the resolving power of ALMA for an ultraluminous galaxy like Arp 220 will allow us to study the ISM properties on a GMC scale—enabling us to probe the properties of the nuclear gas of Arp 220 in great detail.

Single dish and aperture synthesis studies of ^{12}CO and ^{13}CO have shown that the ^{12}CO/^{13}CO 1–0 and 2–1 line intensity ratios are efficient diagnostic tools for large scale ISM properties in galaxies. In particular the ratio between diffuse and self-gravitating gas – as well as the effects of temperature and density in the moderately dense ($n = 10^2 - 10^4$) phase of the molecular gas. Within galaxies there is a general trend of increasing ^{12}CO/^{13}CO 1–0 towards the central region where the gas is warmer and denser (e.g., Wall *et al.* 1993; Aalto *et al.* 1995; Paglione *et al.* 2001). Globally, there is a correlation between the ^{12}CO/^{13}CO 1–0 ratio and the FIR $f(60\mu\mathrm{m})/f(100\mu\mathrm{m})$ flux ratio (e.g., Young & Sanders 1986; Aalto *et al.* 1991b; Aalto 1995). The extreme ratios generally occur in ULIRGs with large dust temperatures. For various discussions of this important diagnostic line ratio see, for instance: Young & Sanders (1986); Aalto *et al.* (1991ab); Casoli *et al.* (1992); Aalto (1995); Hüttemeister *et al.* (2000); Paglione *et al.* (2001); Glenn & Hunter (2001); Tosali *et al.* (2002); Aalto (2005ab).

3. The HCO^+/HCN 1–0 Line Ratio

HCO^+ is suggested by Kohno *et al.* (2001, 2005) to be a tracer of the fraction of the dense gas which is involved in star formation. They compared the HCN/HCO^+ 1–0 line ratio in a selection of Seyfert and starburst galaxies and claim to find that the relative HCO^+ 1–0 luminosity is significantly higher in starbursts. According to Lepp & Dalgarno (1996) a deficiency of HCO^+ is expected near a hard X-ray source—while the HCN abundance may instead increase. Hence, in an AGN dominated nuclear ISM, one expects a brighter HCN line with respect to HCO^+ than in a softer starburst environment. *Lepp and Dalgarno propose using the HCN/HCO^+ ratio as an indicator of what scenario (AGN or starburst) that dominates the luminosity.* Kohno and his collaborators have demonstrated the potential observational usefulness of this line ratio. In Figure 1, a diagnostic diagram is presented showing the HCN/HCO^+ ratio vs. the HCN/CO ratio. Here, composite (i.e. harboring both an AGN and a nuclear staburst) galaxies are mixed in with starbursts, while the pure AGNs show brighter HCN emission relative to both the CO and HCO^+ luminosity. They have applied this to the dusty, edge-on IR-uminous

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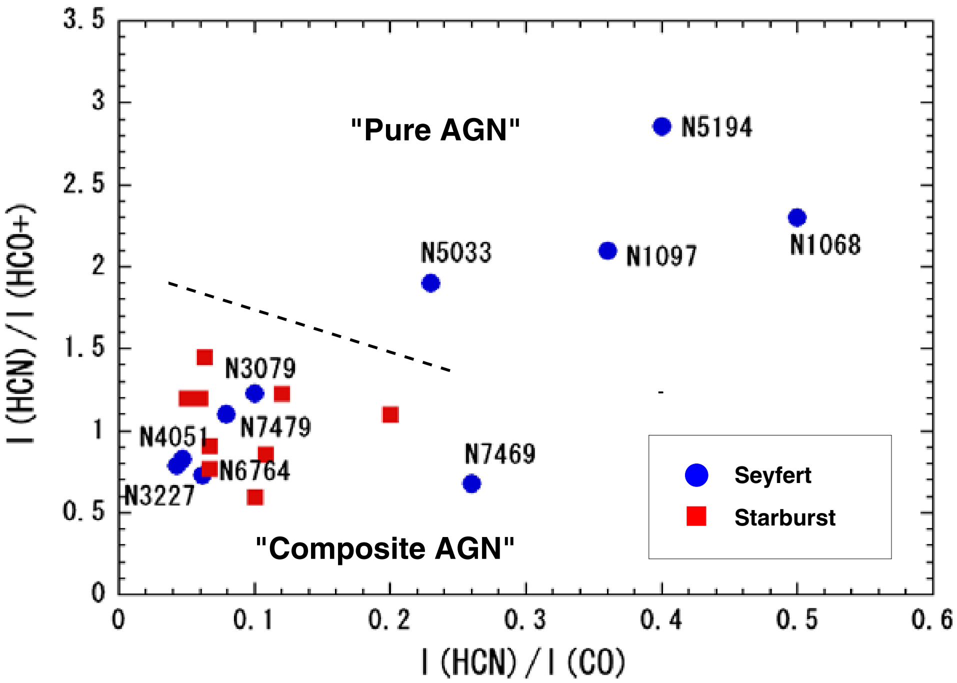

Figure 1. The HCN/HCO$^+$ and HCN/CO line ratios as diagnostic tracers of AGN-Starburst activity (Kohno *et al.* 2001, 2005).

galaxy NGC 4418, and arrived at the conclusion that there is a significant contribution to the luminosity from an AGN since HCN(1–0)/HCO$^+$(1–0)=2.5.

This demonstrates again the importance of using tracers other than HCN to investigate what the dense gas is actually *doing* in the centers of external galaxies. The molecular ISM of the nearby Seyfert 2 galaxy NGC 1068 has been discussed in terms of X-ray dominated chemistry by Usero *et al.* (2004) and is another example where the HCN 1–0 emission outshines that from HCO$^+$ in the nucleus.

4. The HNC/HCN Ratio

HNC, the isomer of HCN, traces gas of equally high density and in dense molecular cloud cores it may be a useful tracer of gas temperature since neutral-neutral chemical models predict that the [HCN]/[HNC] abundance ratio increases with increasing temperature. This is supported by the fact that the measured [HCN]/[HNC] abundance ratio is especially high in the vicinity of the hot core of Orion KL. Most of the temperature dependence is between 10 and 50 K, after which there is a considerable flattening (Schilke *et al.* 1992).

It is therefore surprising that the HCN/HNC J=1–0 intensity ratios are found to be low in luminous galaxies (e.g., Hüttemeister *et al.* 1995; Aalto *et al.* 2002, APHC02) and that the HCN/HNC line ratio appears to increase with galactic luminosity. APHC02 undertook a survey of HNC 1–0 line emission in a sample of 13 luminous IR galaxies ($L_{\rm IR} > 10^{11}$ $L_\odot$) with previously measured HCN luminosities. They found that the HCN/HNC 1–0 ratios vary strongly within the sample—from 1 to $\gtrsim$6. From this we can learn that the actual *properties* of the dense gas vary significantly from galaxy to galaxy, even if their FIR luminosities, HCN luminosities (and global ^{12}CO/HCN 1–0

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luminosity ratios) are similar. Galaxies where I(HCN)=I(HNC) were all found to be luminous Seyfert galaxies. In general, it can be concluded that the *HNC emission is not a reliable tracer of cold (10 K) gas in the center of luminous IR galaxies*, the way it may be in clouds in the disk of the Milky Way. Standard interpretations based on molecular clouds in the disk of the Milky Way cannot be used for inner kiloparsec of luminous galaxies.

As an explanation for the abnormally bright HNC emission, APHC02 suggest that the chemistry is dominated by fast ion-neutral reactions in moderately dense ($n = 10^4 - 10^5\,\mathrm{cm}^{-3}$) PDR-like regions, instead of the neutral-neutral reactions that likely govern the hot dense cores of the Orion cloud. At lower densities, reactions with $HCNH^+$ (HCN and HNC reacts with H_3^+ to form $HCNH^+$) become more important. The ion abundance is higher and once HCN and HNC become protonated, $HCNH^+$ will recombine to produce either HCN or HNC with 50% probability. At higher densities, the ion abundance is likely lower and reactions like HNC + O → CO + NH become more prominent at high temperatures. This scenario is interesting, since the electron and ion abundance is likely higher in PDRs. Therefore, in a PDR chemistry, the connection between HNC abundance and kinetic temperature may also be weak since we there expect the $HCNH^+$ reactions to be important. It is easy to conceive of a chemistry dominated by fast ion-neutral reactions at the heart of an active starburst where there is strong interaction between the activity itself (in photon dominated regions, PDRs) and the surrounding ISM. It is interesting to note that for the nearby galaxy nucleus IC 342 Meier and Turner (2003) find no correlation between the HCN/HNC 1–0 intensity ratio and star forming activity.

Another possible scenario for more luminous galaxies is that, instead of being collisionally excited by H_2, HNC (and perhaps also HCN) is being excited by a number of processes. Both HCN and HNC may become excited via electron collisions (at $X(e) \approx 10^{-5}$) or be pumped by $14\,\mu$m (HCN) or $21.5\,\mu$m (HNC) continuum radiation through vibrational transitions in the degenerate bending mode. Furthermore, we note that some XDR models predict an overabundance of HNC compared to that of HCN (Meijerink & Spaans 2005), which should also be looked into as a possible explanation for bright HNC emission in Seyfert galaxies.

In order to investigate the underlying reasons behind the overluminous HNC emission in luminous galaxies, Aalto *et al.* have searched for HCN and HNC 3–2 emission in a sample of LIRG and ULIRG galaxies with the JCMT telescope. So far, the results show similar excitation for both HNC and HCN in most galaxies studied. Typically, the 3–2 line is fainter than the 1–0 line by at least a factor of 2, suggesting overall densities $\lesssim 5 \times 10^4$ cm^{-3} in the HCN, HNC emitting gas.

4.1. *IR Pumping of HNC?*

An exception to the above finding of subthermally excited HNC is the ultraluminous galaxy Arp 220. For Arp 220, the HNC excitation is highly superthermal with a 3–2/1–0 ratio of $\gtrsim 2$ (Aalto *et al.* 2005c). Wiedner *et al.* find the corresponding HCN to be thermal with ratios close to 0.9. Furthermore, the HNC 3–2 line is significantly brighter than the HCN 3–2 line.

Both HCN and HNC have degenerate bending modes in the IR. For HNC this mode occurs at λ=21.5 μm with an energy level $h\nu$/k=669 K and an A-coefficient of A_{IR}=5.2 s^{-1}. For HCN, the bending mode occurs at λ=14 μm, energy level $h\nu$/k=1029 K and A_{IR}= 1.7 s^{-1} (see, e.g., Aalto *et al.* 1994). Given that there is a sufficient HNC abundance, it is therefore easier to pump the bending state of HNC than HCN. A brief analysis show that the pumping starts to become effective when the IR background reaches an optically thick brightness temperature of $T_{\mathrm{B}} \approx 50$ K.

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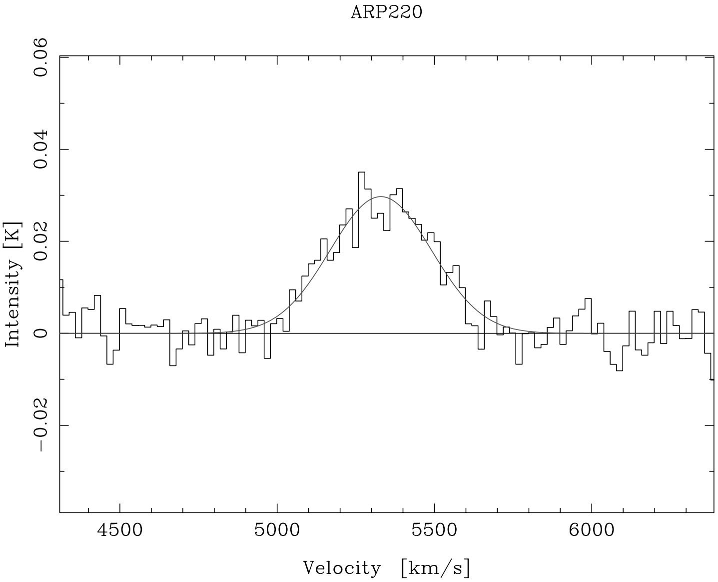

Figure 2. HNC 3–2 JCMT spectrum of Arp 220. Antenna temperature scale is in T_A^* (Aalto *et al.* 2005c).

4.2. *Pumping of HNC and HCN in Arp 220*

Soifer *et al.* (1999) discuss 24.5 μm brightness temperatures of Arp 220 in excess of 85 K. This result is model and source size dependent—the actual temperatures may in fact be higher. The HNC 3–2 line intensity is greater than that of HCN 3–2, which may indicate that the HNC line is affected by IR-pumping. In extremely cold ($\lesssim 10$ K) and dense conditions it is possible that X[HNC]>X[HCN]—conditions such as these may occur in the hearts of cold dark clouds (e.g Ziurys and Turner 1986). In the ULIRG ARP 220 however, the ISM conditions are very unlike those of cold dark clouds with an extreme starburst and average molecular gas temperatures exceeding 40 K (e.g Sakamoto *et al.* (1999) and an intense IR radiation field (Soifer *et al.* 1999). In contrast to HCN, CN is subthermally excited—indicating moderate densities around 5×10^4 cm^{-3}—while (if collisionally excited) the HCN line ratios suggest densities two orders of magnitude greater, $10^6 - 10^7$ cm^{-3}. How can we reconcile these two apparently conflicting results? Perhaps the CN emission is emerging from moderately dense PDRs at the surfaces of very dense clumps from which the HCN emission arises. Alternatively, the CN emission may reflect the density of the gas—while (at least a fraction of) the HCN emission may be pumped. Further excitation studies of HCN, HNC and CN and other high density tracer molecules are necessary to distinguish between these two scenarios.

5. CN and PDRs in Luminous Galaxies

The radical CN is another tracer of dense gas, with a somewhat lower (by ~5×) critical density than HCN. The abundance of the CN radical becomes enhanced at the inner edge of a PDR (at an A_V of about 2 magnitudes). At larger depths into the cloud the CN abundance radically declines and the [HCN]/[CN] abundance ratio increases (e.g., Jansen *et al.* 1995). Observations of the CN emission toward the Orion A molecular clouds (Rodríguez-Franco *et al.* 1998) show that the morphology of the CN emission is dominated by the ionization fronts of H II regions. The authors conclude that this

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molecule is an excellent tracer of regions affected by UV radiation. Thus, the emission from the CN molecule should serve as a measure of the relative importance of gas in PDRs.

Aalto *et al.* (2002) also conducted a CN 1–0 (and 2–1) survey in the same galaxies they surveyed for HNC (see above). The goal was to probe the PDR phase of the molecular ISM of which CN should be a reliable tracer. Also in this study, the HCN/CN 1–0 intensity ratios show significant variation—ranging from 0.5 to $\gtrsim 6$. There is a surprising trend of *decreasing* CN luminosity with increasing FIR luminosity (but this trend needs to be confirmed with a larger sample). This is unexpected, since the luminosity of ULIRGs is suspected to be largely dominated by massive starbursts. It is also noteworthy that another classical PDR tracer is weak in ULIRGs: the [C II] 158 μm fine structure line is found to be unexpectedly faint compared to other, less FIR luminous, starburst galaxies like NGC 3690 (e.g., Luhman *et al.* 1998). Malhotra *et al.* (1997) report a decreasing trend in $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ with increasing $f(60)/f(100)$ μm flux ratio. Several possible explanations for the [C II] faintness have been brought forward (e.g., Malhotra *et al.* 1997; Luhman *et al.* 1998; van der Werf 2001). The PDRs may be quenched in the high pressure, high density environment in the deep potentials of the ULIRGs and the H II regions exist in forms of small-volume, ultracompact H II regions that are dust-bounded. The [C II] line may become saturated either in low density ($n \propto 10^2$ cm^{-3}) regions of very high UV fields ($G_0 \propto 10^3$) or in dense ($n \propto 10^5$ cm^{-3}) regions of more moderate UV fields ($G_0 = 5 - 10$). A soft UV field from an aging starburst is another possibility, and a higher dust-to-gas ratio would also decrease the expected $F_{[\mathrm{C\,II}]}/F_{\mathrm{FIR}}$ ratio.

There is not a one-to-one correspondence between CN and [C II] faint galaxies, but the general trend appears similar and should be further investigated. This emphasizes the need for care when using nearby, significantly less luminous, systems as prototypes for all starbursts. The molecular interstellar medium of ULIRGs seems to have different properties than that of more modest bursts and we still have to find out whether the cause is evolutionary or whether the bursts are intrinsically different in the ULIRGs. The presence of an AGN may also significantly affect the properties of the nuclear ISM.

5.1. *CN in Arp 299*

In the luminous merger Arp 299 there are three main regions of activity: the two galactic nuclei (IC 694 and NGC 3690) and the overlap region (where the galactic disks come together). Arp 299 has been studied in ^{12}CO, ^{13}CO 1–0, 2–1, HCN 1–0 at high resolution (Aalto *et al.* 1997; Aalto *et al.* 1999; Casoli *et al.* 1999). The dense gas, as traced by HCN, was found to be abundant in the three main regions of activity.

Aalto *et al.* imaged the CN 1–0 emission with the OVRO array with the goal of measuring the HCN/CN line ratio in the three main molecular emission regions. As is evident in Figure 3, *the CN 1–0 emission peaks towards the nucleus of IC 694 and is also bright in the overlap region, while no emission can be detected towards the center of NGC 3690.* A preliminary estimate of the HCN/CN ratios suggest that the HCN/CN ratio exceeds 5 in the NGC 3690 nucleus. This reveals that the properties of the molecular ISM in the two nuclei is quite different—something already indicated in the high resolution ^{13}CO data. The fact that bright CN emission is found in the extended emission of the overlap region shows that it is not only confined to starbursts in the inner regions of galaxies. Why is there no CN detection towards the nucleus of NGC 3690 despite bright HCN emission? From NIR and optical studies (Alonso Herrero *et al.* 2000) the starburst in NGC 3690 is intermediate (age ~7.5 Myrs) in age between IC 694 (11 Myrs) and the overlap region (4–5 Myrs)—so there appears to be no obvious connection to the age of the starburst. *However, if the nucleus of NGC 3690 is deeply dust-enshrouded and*

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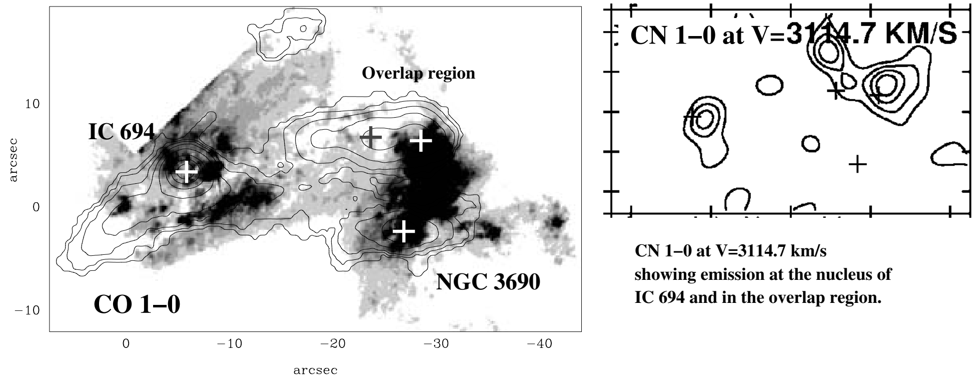

CN 1–0 at V=3114.7 km/s
showing emission at the nucleus of
IC 694 and in the overlap region.

Figure 3. The CN 1–0 emission (OVRO) towards the luminous merger Arp 299. The crosses mark the radio continuum peak positions of the IC 694 and NGC 3690 nuclei and in the overlap region.

compact it be unreachable by optical or near infrared diagnostic tools—then NGC 3690 may harbor a very young starburst or an AGN. In this context the CN-deficiency is the result of large masses of dust absorbing UV emission from the nuclear activity. From recent water maser observations, there is evidence of the presence of a deeply buried AGN in NGC 3690—and perhaps also in IC 694 (e.g., Della Ceca *et al.* 2002, Henkel *et al.* 2005). The CO emission is compact and unresolved in the OVRO beam towards the NGC 3690 nucleus, consistent with deeply buried activity (e.g., Aalto *et al.* (1997)).

Perhaps the cause behind the (apparently) faint CN emission in luminous galaxies is because the activity, and molecular distribution, becomes more nuclear with increasing luminosity. Compact, high-A_V regions are then expected to have bright HCN—but faint CN emission. The eastern nucleus of Arp 220 is another example of a CN-faint compact nucleus (see below).

6. HC_3N Tracing Young, Compact Starburst Activity?

From spectral line shapes one can deduce a difference in the HCN/CN 1–0 line ratio between the two nuclei of the ultraluminous merger Arp 220. Most of the CN emission appears to be emerging from the western nucleus while HCN 1–0 is coming from both nuclei (Aalto *et al.* 2002). The compact, deeply enshrouded eastern nucleus shows little or no CN emission, while instead it has a strong HC_3N signal (APHC02). Rodríguez-Franco *et al.* (1998) show that the emission from HC_3N is bright toward hot, dense cores, while the $[HC_3N]/[CN]$ abundance ratio is only 10^{-3} in PDRs. Thus the eastern nucleus seems to be in an earlier evolutionary phase where star formation has just begun.

7. Concluding Remarks

Molecular line ratios are showing interesting, and sometimes surprising, results as tracers of the chemistry and physical conditions of the molecular gas in the inner regions of active galaxies. They are showing great potential in distinguishing between types of nuclear activity—as well as between evolutionary stages of a starburst. Together with other extinction-free tracers such as radio continuum, radio recombination lines and X-rays, the diagnostic value of the line ratios will be further enhanced. With the resolving power and sensitivity of the ALMA array, we will be able to study these regions in even more detail. This will also increase the complexity of the required chemical and radiative

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transport models hopefully intensifying contacts and collaborations between observers and theorists.

Acknowledgements

I am grateful to many people for discussions and advice. Most recently these include John Black, Henrik Olofsson, Peter Schilke, Martina Wiedner and Marco Spaans.

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