THE IMPACT OF STAR FORMATION AND ACTIVE NUCLEI ON THE INTERSTELLAR MEDIUM IN ULTRALUMINOUS INFRARED GALAXIES

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Abstract. The energy input into the interstellar medium in Ultraluminous Infrared Galaxies (ULIRGs) is enormous, regardless of the nature of the power source. I discuss some of the major consequences for the structure and energetics of the ISM in these galaxies. Observationally, the column densities in the nuclear regions of ULIRGs are known to be very high, which makes distinguishing starbursts from AGN quite difficult. The level of energy and momentum injection means that the pressure in the ISM must be extremely high, at least $3-4$ orders of magnitude larger than in the local ISM or typical giant molecular clouds. It also means that the luminosity of GMCs in ULIRGs must be very high, as they must radiate many times their binding energy over their lifetimes. I briefly review the influence which X-ray irradiation can have on the ISM in AGN-powered ULIRGs. Finally, I show that the presence of PAH features in ULIRGs does not imply that they must be starburst-dominated, since at the column densities and pressures typical of the ISM in ULIRGs PAHs can survive even at tens of parsec distances from the AGN.

1. Introduction

The observed characteristics of ULIRGs (luminosities $L_{\text{IR}} \gtrsim 10^{12} L_{\odot}$, size scales $r \lesssim \text{a few hundred pc}$) imply typical energy densities $u \sim 10^{-8}$ erg cm$^{-3}$. This is $3-4$ orders of magnitude larger than the typical energy densities (in gas, photons, and cosmic rays) in the interstellar medium (ISM) in the solar neighborhood (e.g., Jura 1987). In this review, I will discuss how both the production and release of such energies is expected to impact the ISM. I will concentrate on those aspects most relevant to ULIRGs, i.e.,
very powerful starbursts and luminous active galactic nuclei (AGN). Due to space limitations, the discussion is necessarily terse. In particular, the referencing is by no means complete, and should be regarded largely as a pointer to the relevant literature (a good place to start is the recent review by Sanders & Mirabel 1996); my apologies to those whose contributions have of necessity been left out.

2. Basic Parameters

2.1. STARBURST:

*Bolometric Luminosity* The frequency-integrated energy output from a starburst can be approximated as

$$L_{\text{bol}} \sim 10^{10} \left( \frac{\dot{M}}{M_\odot \text{yr}^{-1}} \right) \left( \frac{\Delta t}{10^8 \text{yr}} \right)^{2/3} \left( \frac{m_l}{1 M_\odot} \right)^\alpha \left( \frac{m_u}{45 M_\odot} \right)^{0.37} L_\odot$$

for a constant star formation rate (SFR) burst of age \(\Delta t\), upper and lower mass cutoffs \(m_u\) and \(m_l\), and \(\alpha = 0.23\) for \(m_l < 1 M_\odot\) (Scoville & Soifer 1991; see also Smith, Lonsdale, & Lonsdale 1998). (Here and frequently throughout this review, adopted scalings with mass, density, etc. should be regarded with the caution usually reserved for possibly rabid housepets.) This implies that powering ULIRGs by star formation requires

$$\dot{M} \sim 100 \left( \frac{L_{\text{bol}}}{10^{12} L_\odot} \right) \left( \frac{\Delta t}{10^8 \text{yr}} \right)^{-0.67} M_\odot \text{yr}^{-1}$$

modulo the details of the assumed initial mass function. Thus ULIRGs must have SFR in excess of \(100 M_\odot \text{yr}^{-1}\), barring extreme assumptions about the IMF.

*Lyman Continuum Photons* The number of Lyman continuum (\(E \geq 13.6\) eV) photons produced per second by a starburst is approximately (Scoville & Soifer 1991)

$$N_{\text{LyC}} \sim 10^{53} \left( \frac{\dot{M}}{M_\odot \text{yr}^{-1}} \right) \left( \frac{m_l}{1 M_\odot} \right)^\alpha \left( \frac{m_u}{45 M_\odot} \right)^\beta \text{s}^{-1}$$

(\(\beta = 2, m_u < 45 M_\odot; \beta = 1.35, m_u > 45 M_\odot\)), where I have again assumed a constant SFR burst with an age of \(10^8\) years. Thus

$$N_{\text{LyC}} \sim 10^{55} \left( \frac{L_{\text{bol}}}{10^{12} L_\odot} \right) \text{s}^{-1}$$

for a typical ULIRG. Since the radiation is stellar in origin, the spectrum of radiation is sharply cutoff above a few tens of eV.
Supernova Rate

The implied supernova rate for a starburst-powered ULIRG is

\[ \nu_{\text{SN}} \sim 1 \left( \frac{L_{\text{bol}}}{10^{12} L_\odot} \right) \text{yr}^{-1}. \]  

(5)

This rate is not very sensitive to the assumptions made about the IMF, since the predecessors of most SNe have \( M \sim 10 M_\odot \).

2.2. AGN:

Bolometric Luminosity

The accretion luminosity for an accreting black hole (presumed, for many reasons, to be the power source in AGN) which is converting rest-mass energy to radiation with an efficiency \( \epsilon \) is

\[ L_{\text{acc}} = 1.5 \times 10^{12} \left( \frac{\epsilon}{0.1} \right) \left( \frac{\dot{M}}{M_\odot \text{yr}^{-1}} \right) L_\odot \]  

(6)

independent of the mass of the hole. However, the Eddington limit (the luminosity above which radiation pressure will halt accretion for steady, spherically-symmetric flow) is

\[ L_{\text{Edd}} \approx 3.4 \times 10^{11} \left( \frac{\epsilon}{0.1} \right) \left( \frac{M_{\text{BH}}}{10^7 M_\odot} \right) L_\odot. \]  

(7)

If we require \( L_{\text{acc}} < L_{\text{Edd}} \), we must have

\[ M_{\text{BH}} > 4 \times 10^7 \left( \frac{\epsilon}{0.1} \right) \left( \frac{\dot{M}}{M_\odot \text{yr}^{-1}} \right) M_\odot. \]  

(8)

Lyman Continuum Photons

The typical spectrum of an AGN is a power-law in energy, with a flux density \( f_\nu \propto \nu^{-\alpha} \), with \( \alpha \sim 1 \) (i.e., the spectrum is flat, with approximately equal energy per decade of photon energy). For unobscured (Type 1) AGN, the X-ray luminosity \( L_x \approx 0.1 L_{\text{bol}} \), and the spectral index in the hard X-ray regime \( \alpha \approx 0.7 \). The fraction of energy emitted in the 2-10 keV band decreases slowly with increasing luminosity (see the summary in Mushotzky, Done, & Pounds 1993). For a spectrum with \( \nu f_\nu = \text{constant from 1 eV to 100 keV}, \) the number of Lyman continuum photons is

\[ N_{\text{LyC}} \sim 10^{55} \left( \frac{L_{\text{bol}}}{10^{12} L_\odot} \right) \text{s}^{-1} \]  

(9)

essentially identical to the number produced by a starburst. Although an AGN spectrum extends to far higher energies than that of a starburst, most of the ionizing photons by number are between 13.6 and 100 eV, just as in a starburst.
3. Fueling

3.1. STARBURST:

Forming stars at a rate \( \dot{M}_s \ M_\odot \text{ yr}^{-1} \) requires gas utilization at a rate

\[
\dot{M} = \frac{\dot{M}_s}{\epsilon_s}
\]

(10)

where \( \epsilon_s \) is the efficiency of star formation, i.e., the fraction of the mass of a star-forming cloud which is actually transformed into stars in the cloud’s lifetime. The observed value \( \epsilon_s \sim 0.01 - 0.1 \) in Galactic molecular clouds. (Note, however, that in order to form a bound stellar system, such as a globular cluster, simple binding energy arguments show that the efficiency must be much higher, \( \epsilon_s \gtrsim 0.4 \); if the so-called “proto-globular clusters” seen, for example, in NGC 4038/4039 [Whitmore & Schweizer 1995] are in fact bound systems, then the SFE must have been quite high.) Of this gas used by star formation, an amount

\[
\dot{M}_{\text{eff}} = \frac{1 - \epsilon_s}{\epsilon_s} f_{\text{dis}} \dot{M}_s + f_{\text{rem}} \dot{M}_s \equiv f \dot{M}_s
\]

(11)

is lost from the system. In this equation \( f_{\text{dis}} \) is the fraction of the non-stellar remainder of the star-forming cloud which has either been blown entirely out of the system (e.g., in a galactic superwind: see §4), or is either too hot or too dispersed to reform into star-forming clouds on the characteristic timescale of the burst; \( f_{\text{rem}} \) is the fraction of the stellar mass that is in the form of stellar remnants or stars which have masses too low for them to evolve off the main sequence during the lifetime of the burst. The true gas usage timescale is thus

\[
\tau_s = \frac{M_{\text{gas}}}{\dot{M}_{\text{eff}}} = \frac{M_{\text{gas}}}{f \dot{M}_s} = 10^7 \text{ yr} \left( \frac{M_{\text{gas}}}{10^9 M_\odot} \right) \left( \frac{100 M_\odot \text{ yr}^{-1}}{M_s} \right) f^{-1}.
\]

(12)

The values of both \( f_{\text{dis}} \) and \( f_{\text{rem}} \) depend strongly on \( \Delta t \). For example, for a burst duration \( \Delta t = 10^7 \) yr, only stars with \( M \gtrsim 13 M_\odot \) have evolved off the main sequence. For a Miller-Scalo (1979) IMF with \( m_l = 10, m_u = 62, f_{\text{rem}} \sim 0.4 \); if the lower mass limit is reduced to \( m_l = 5 \), \( f_{\text{rem}} \sim 0.7 \). If \( \epsilon_s = 0.1 \), \( f_{\text{rem}} = 0.5 \), and \( f_{\text{dis}} = 0.5 \) (as is suggested by observations in the case of M82: see §4.1), then \( f = 5 \), and gas is effectively consumed at a much greater rate than that at which it is formed into stars. It must be emphasized again, however, that the effective values of \( f_{\text{rem}} \) and \( f_{\text{dis}} \) are uncertain, depending not only on the duration of the burst but, for \( f_{\text{dis}} \), on the physical conditions in the ISM, since this will presumably determine the recycling time for the gas.
3.2. AGN:

The fueling requirements for AGN-powered ULIRGs are comparatively trivial: for the required rate $\dot{M} \sim 1 \, M_\odot \, yr^{-1}$, the lifetime of the activity is

$$\tau_{\text{AGN}} \sim 10^9 \, yr \left( \frac{M_{\text{gas}}}{10^9 \, M_\odot} \right) f_{\text{loss}}^{-1}$$

(13)

where $f_{\text{loss}} \geq 1$ takes account of mass that is lost without accretion in the form of winds, etc. Of course, it is exceedingly unlikely that the gas reservoir is simply quiescently orbiting the black hole, waiting to be accreted.

4. Superbubbles and Superwinds

4.1. STARBURST:

Massive stars input both energy and momentum into the ISM, through radiation, stellar winds and supernova blast waves. In systems with high rates of star formation, this input can have dramatic impact on the dynamics of the ISM. In standard stellar wind theory (Weaver et al. 1977), the wind produces a hot shocked bubble in the ambient ISM; the swept-up ISM at the boundary will collapse to a thin shell provided the density is high enough for cooling to be efficient.

In regions with many young, massive stars, a much larger scale version of such a wind bubble may result, as multiple stellar winds and especially supernovae contribute to the development of a single large cavity. The evolution of such “superbubbles” can be largely understood simply by extending stellar wind bubble theory, scaling upward to the mass and energy input from a starburst (Chevalier & Clegg 1985; MacLow & McCray 1988; Tomisaka & Ikeuchi 1988). Scaled to a canonical supernova rate $\nu_{\text{SN}} \sim 1 \, yr^{-1}$, the mechanical energy and mass input rates are

$$L_{\text{SN}} \sim 3 \times 10^{43} \left( \frac{\nu_{\text{SN}}}{1 \, \text{yr}^{-1}} \right) \left( \frac{E_{\text{SN}}}{10^{51} \, \text{erg}} \right) \text{erg s}^{-1}$$

(14)

$$\dot{M}_{\text{SN}} \sim 10 \left( \frac{\nu_{\text{SN}}}{1 \, \text{yr}^{-1}} \right) M_\odot \, \text{yr}^{-1}$$

(15)

For a uniform ambient density $n_o$, the radius, expansion velocity, internal pressure, and thermal energy of the superbubble are (e.g., Heckman et al. 1996)

$$R \sim 1.1 \left( \frac{L_{43.5}}{n_o} \right)^{1/5} t_7^{3/5} \text{ kpc}$$

(16)

$$V = \dot{R} \sim 200 \left( \frac{L_{43.5}}{n_o} \right)^{1/5} t_7^{-2/5} \text{ km s}^{-1}$$

(17)
\[ \hat{P} = \frac{P}{k} \sim 5 \times 10^6 L_{43.5}^{2/5} n_o^{3/5} t_7^{-4/5} \text{ cm}^{-3} \text{ K} \]  
(18)

\[ E_{\text{th}} \sim 4 \times 10^{57} L_{43.5} t_7 \text{ erg}. \]  
(19)

Finally, the soft X-ray (ROSAT-band) luminosity is approximately

\[ L_x \sim 10^{42} L_{43.5}^{33/35} n_o^{17/35} t_7^{19/35} \text{ erg s}^{-1}; \]  
(20)

this includes the effects of evaporation into the interior of the bubble. In these equations the mechanical luminosity of the OB association (approximated as constant) is \( L_{SN} = 3 \times 10^{43} L_{43.5} \text{ erg s}^{-1} \) and the age of the superbubble is \( t = 10^7 t_7 \text{ yr} \).

The expansion velocity (17) is generally supersonic, so the superbubble drives a shock into the surrounding ISM. The resulting shock luminosity depends on both the shock velocity and the ambient density:

\[ L_{sh} \approx 2 \times 10^{40} V_{100}^3 n_o A_{sh} \text{ erg s}^{-1} \sim 2 \times 10^{42} L_{43.5} \text{ erg s}^{-1} \]  
(21)

where the shock velocity \( V_{sh} = 100V_{100} \text{ km s}^{-1} \) and the shock area \( A_{sh} \) is in kpc\(^2\) (Dopita & Sutherland 1996); the second line assumes \( V_{sh} \) is equal to the bubble expansion speed and uses equations (16) and (17). For shock speeds in the range \( V_{sh} \sim 10^2 - 10^3 \text{ km s}^{-1} \), the resulting H\(\alpha\) luminosity \( L_{H\alpha} \sim 0.01 L_{sh} V_{100}^{-0.6} \). The [O III] \( \lambda 4959 + \lambda 5007 \) line luminosity (including the contribution from the UV precursor) is comparable to the H\(\alpha\) luminosity at \( V_{100} \approx 2 \) and gets relatively stronger as the shock speed increases, with the ratio scaling approximately as \( V_{sh}^{2.3} \) (Dopita & Sutherland 1996).

The finite scale height of the gas disk means that the superbubble can expand entirely out of the disk, provided it is energetic enough. Such “blowout” will occur if the dimensionless parameter

\[ D = \frac{L_{SN}}{L_{ISM}} \sim 10^4 \left( \frac{H}{100 \text{ pc}} \right)^{-2} \left( \frac{\hat{P}_{ISM}}{10^7 \text{ cm}^{-3} \text{ K}} \right)^{-3/2} n_o^{1/2} > 100 \]  
(22)

(MacLow & McCray 1988) where \( L_{ISM} = P_{ISM} H^3/t_{dyn} \) is the “luminosity” of the ISM over the dynamical timescale \( t_{dyn} \), defined as the time for the bubble to reach a radius of comparable to the scale height \( H \) of the gas layer (cf. equation [16]). Once the superbubble shell reaches an altitude \( Z \lesssim \text{a few } H \), it will begin to accelerate along the density gradient and fragment due to Rayleigh-Taylor instabilities. Provided this occurs on a timescale less than the lifetime of the OB association powering the supershell, the continuous injection of energy and momentum from the association will lead to the development of a galactic wind.

There is extensive evidence for such large-scale galactic “superwinds” (e.g., Heckman, Armus & Miley 1990; Veilleux et al. 1994; Heckman et al.
1996), from morphologies, kinematics, and the presence of density/pressure profiles in reasonable agreement with the predictions of wind models (although there is not always agreement on the latter: see Veilleux et al. 1994). In the prototypical ULIRG Arp 220, the superbubble does not appear to have blown out, as the morphology and kinematics suggest a confined, shocked bubble. The starburst galaxy M82, on the other hand, appears to possess a freely expanding wind. Suchkov et al. (1996) argue that the wind in M82 must be mass-loaded, i.e., the mass flux in the wind is enhanced by a factor of \( \sim 5 \) over the SNe mass deposition rate, by entrainment or evaporation of interstellar material. The implied mass lost through the wind is \( M_W \sim 5 \times 10^7 t_7 M_\odot \), which is comparable to the total molecular gas mass present in the nucleus. If this is typical of superwinds, then the fraction of available gas which is lost from the system is large, \( f_{\text{dis}} \sim 0.5 \).

4.2. AGN:

The possibility that AGN might drive powerful nuclear winds dates back at least to Weymann et al. (1982). More recently, this idea has been revived by Smith (1993, 1996) to explain the kinematics of the NLR and as a mechanism for cloud confinement. In a very provocative paper, Bicknell et al. (1998) have proposed that the radio jets in Seyfert galaxies are actually dominated by thermal plasma, with mechanical luminosities of order \( L_{\text{mech}} \sim 0.1 L_{\text{bol}} \); the winds start off only mildly relativistic. Bicknell et al. make specific application to the excitation of the NLR in NGC 1068, and find additional support for this model from study of regions of jet-cloud interaction within the NLR. Interestingly, in a study of soft X-ray emission from large-scale nuclear outflows in a sample of nearby, edge-on Seyfert galaxies, Colbert et al. (1998) conclude that the outflows must be dominated by thermal plasma. This is an idea which is clearly deserving of far more study. If correct, it would replace the still unanswered question “Why are some objects radio-loud and others radio-quiet?” with another: “Why are some jets dominated by nonthermal plasma?”

5. Global Energetics of the ISM

Most ULIRGs are inferred to possess large quantities \( (M \gtrsim 10^9 M_\odot) \) of high-density gas \( (n_H \sim 10^4 \text{ cm}^{-3}) \), characterized by large velocity dispersions \( (\sigma \text{ up to } \sim 100 \text{ km s}^{-1}) \); see e.g., Tacconi, this volume. This implies that the energy dissipation rate within the ISM is very large: dimensionally,

\[
\dot{E}_{\text{kin}} \sim \eta \frac{M}{R} \sigma^3 \sim 6 \times 10^{42} \eta \left( \frac{M}{10^9 M_\odot} \right) R_{100}^{-1} \sigma_7^3 \text{ erg s}^{-1}
\]  

(23)
where $R = 100R_{100}$ pc, $\sigma = 100\sigma_7$ km s$^{-1}$, and the coefficient $\eta \lesssim 1$ (e.g., MacLow 1998). Since the total non-rotational kinetic energy of the ISM is

$$E_{\text{kin}} \sim \frac{1}{2} M \sigma^2 \sim 10^{56} \left( \frac{M}{10^9 M_\odot} \right) \sigma_7^2 \text{ erg},$$

(24)

the energy loss timescale is

$$t_{\text{diss}} \sim \frac{E_{\text{kin}}}{\dot{E}_{\text{kin}}} \sim 5 \times 10^5 \frac{R_{100}}{\eta \sigma_7} \text{ yr.}$$

(25)

Equivalently, since the inferred area filling factor of dense ISM in ULIRGs is close to unity (e.g., Scoville, Yun, & Bryant 1997), the energy loss timescale (assuming strongly dissipative collisions) $t_{\text{diss}} \sim R/\sigma \sim 10^6 R_{100}/\sigma_7$ yr, essentially identical with the above estimate. Since the energy dissipation timescale is much shorter than the probable lifetime of the ULIRG, the random bulk motions of the ISM must be continuously powered.

5.1. STARBURST:

As noted in §4, the mechanical energy input from supernovae for a $L = 10^{12}L_{12}$ $L_\odot$ ULIRG is

$$L_{\text{SN}} \sim 3 \times 10^{43} \left( \frac{\nu_{\text{SN}}}{1 \text{ yr}^{-1}} \right) \left( \frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \text{ erg s}^{-1}$$

(26)

which is adequate to supply the necessary kinetic energy provided that a substantial fraction is absorbed by the dense ISM (and that momentum transfer to the clouds is reasonably efficient); given the large area covering factors inferred in ULIRGs (e.g., Scoville et al. 1997), this seems quite reasonable.

5.2. AGN:

Supporting the mechanical luminosity of the ISM requires either (1) relatively efficient conversion of radiation to mechanical energy, or (2), mechanical (momentum) input from an AGN wind, as discussed above, with $L_{\text{mech}} \gtrsim 0.1L_{\text{bol}}$.

6. Dynamical Support by Radiation Pressure

As we have just seen, there is enough energy available from either a starburst or an AGN to maintain the energy loss rates estimated for the ISM in ULIRGs. A related topic is the momentum input rate. Scoville et al. (1995) suggested that radiation pressure might contribute significantly to
the support of the gas against gravity in the $z = 2.3$ ULIRG F10214+4724, in order to reconcile the CO-derived gas mass with a dynamical mass (estimated from the CO source size and line width) which is an order of magnitude smaller.

Assume that a cloud at radius $r$ absorbs all of the incident flux (and therefore photon momentum) incident upon it from the central source of radiation. In equilibrium, the condition that the radiation provide enough pressure to support the cloud against gravity is just

$$\frac{GM\mu m_H N_H}{r^2} = \frac{L}{4\pi r^2 c}$$

(27)

where $M$ is the total mass enclosed within radius $r$, $\mu$ is the mean atomic weight in units of the hydrogen mass $m_H$, and $N_H$ is the hydrogen column density through the cloud. Simple rearrangement shows that the cloud column density which can be supported is

$$N_{\text{rad}}^H \sim \frac{L}{4\pi G \mu m_H M} \simeq 3.5 \times 10^{22} \left(\frac{L/M}{10^3}\right) \text{ cm}^{-2}$$

(28)

which depends on the luminosity to mass ratio, here expressed in solar units. (Note that although I have done the calculation by balancing the radial gravitational attraction against the radiation pressure from a central source, the identical result is obtained by calculating the column which can be vertically supported above a radiating slab, which may be a more relevant geometry for starburst-powered ULIRGs).

The limiting column density which can be supported is much smaller (by a factor $10 - 100$) than the area-averaged molecular column densities which have been derived in the nuclei of ULIRGs, for which the values of $L/M$ generally lie in the range $10^2 - 10^3$, suggesting that radiation pressure support is not important. The expression for the critical column (28) assumes that the photons give up all of their momentum immediately, in other words, it has been assumed that the ISM is optically thin to the re-radiated photons (generally in the mid- to far-infrared). If the ISM is optically thick to these photons, then multiple scattering of the radiation will occur. However, this will not increase the column which can be supported. Assume that the medium is very optically thick, so that a large number of scatterings occur. In this case the radiation field will become nearly isotropic. The degree of anisotropy (which determines how much work the radiation field can do against gravity) is then set by the net flux outward; this is (in spherical geometry) precisely $L/4\pi R^2$, and so the value of $N_{\text{rad}}^H$ is unaltered.
7. Pressure in the ISM

In any model for ULIRGs, an inevitable result is that the pressure in the ISM must be extremely high:

- Simply from the derived gas densities and observed turbulent velocities, the inferred turbulent pressures must be high:
  \[ \tilde{P}_{\text{turb}} \sim 5 \times 10^8 \left( \frac{n}{10^4 \text{ cm}^{-3}} \right) \left( \frac{\sigma_{\text{turb}}}{30 \text{ km s}^{-1}} \right)^2 \text{ cm}^{-3} \text{ K.} \]  

  (29)

- If the nuclear (\( R \sim 100 \text{ pc} \)) ISM essentially radiates like a blackbody, as proposed by Downes & Solomon (1998), then the radiation pressure in this region
  \[ P_{\text{rad}} = \frac{u}{3} \sim \frac{L_{\text{bol}}}{12\pi R^2 c} \]  

  (where \( u \) is the radiation energy density) and so therefore
  \[ \tilde{P}_{\text{rad}} \sim 3 \times 10^8 L_{12} R_{100}^{-2} \text{ cm}^{-3} \text{ K.} \]  

  (31)

- In an AGN-powered ULIRG, the pressure of radiation from the central source of luminosity will force the gas pressure to large values:
  \[ \tilde{P}_{\text{rad}} \sim 8 \times 10^7 \left( \frac{f_{\text{abs}}}{0.1} \right) L_{12} R_{100}^{-2} \text{ cm}^{-3} \text{ K} \]  

  (32)

  where \( f_{\text{abs}} \) is the fraction of the incident radiation which is absorbed in a thickness \( \delta r \ll r_c \), the cloud radius (see Barvainis et al. 1997).

- In a starburst-powered ULIRG, with enough energy input from SNe to drive a superwind, the pressure in the injection region (i.e., on the spatial scale of the starburst) is
  \[ P_o \sim 0.1 \dot{M}^{1/2} L_{SN}^{1/2} R_{SB}^{-2} \]  

  (Chevalier & Clegg 1985) where \( R_{SB} \) is the radius of the starburst region; hence
  \[ \tilde{P}_o \sim 3 \times 10^8 \left( \frac{\dot{M}_{\text{SN}}}{M_\odot \text{ yr}^{-1}} \right) \left( \frac{L_{\text{SN}}}{10^{43.5} \text{ erg s}^{-1}} \right) \left( \frac{R_{SB}}{100 \text{ pc}} \right)^{-2}. \]  

  (34)

All of these estimates agree to order of magnitude, implying that the pressure in the ISM \( \tilde{P}_{\text{ISM}} \sim 10^8 \text{ cm}^{-3} \text{ K} \) in ULIRGs. This is 3 – 4 orders of magnitude larger than the pressure in the average ISM in the solar neighborhood; only the densest cloud cores approach such high pressures. Similarly high pressures have been inferred in more modest starburst galaxies such as NGC 1808 and NGC 3256 (e.g., Aalto et al. 1994, 1995).
8. Local Energetics: Energy Input to Molecular Clouds

8.1. STARBURST:

The power input from an OB association in the form of radiation, stellar winds, and supernovae is

\[ \dot{E}_{\text{OB}} \sim 6 \times 10^{35} N \ast \text{erg s}^{-1} \]  

(McCray & Kafatos 1987) where \( N \ast \) is the number of stars in the association with \( M > 8 M_\odot \). For lower and upper stellar mass cutoffs of \( m_l = 1 \) and \( m_u = 60 M_\odot \), respectively, (which gives 1 SNe for every \( \sim 100 M_\odot \) turned into stars) the energy input to the cloud from which the association formed over the cloud’s lifetime \( \Delta t \) is

\[ E_{\text{OB}} \sim 5 \times 10^{51} \left( \epsilon_\ast \right) \left( \frac{M_c}{10^5 M_\odot} \right) \left( \frac{\Delta t}{10^7 \text{yr}} \right) \text{erg} \]  

where \( M_c \) is the cloud mass and \( \epsilon_\ast \) is the star formation efficiency as before.

The cloud binding energy (for mean cloud density \( n_H = 10^4 n_4 \text{ cm}^{-3} \))

\[ E_B \sim \frac{GM_c^2}{r_c} \sim 2 \times 10^{50} \left( \frac{M_c}{10^5 M_\odot} \right)^{5/3} n_4^{1/3} \text{erg} \]  

the ratio of energy input to binding energy is thus

\[ \frac{E_{\text{OB}}}{E_B} \sim 25 \left( \frac{\epsilon_\ast}{0.01} \right) \left( \frac{M_c}{10^5 M_\odot} \right)^{-2/3} n_4^{-1/3} \left( \frac{\Delta t}{10^7 \text{yr}} \right) \]  

which depends relatively weakly on the assumed cloud parameters. Thus, in principle, only a few percent of the available power needs to be input to the cloud in order to disperse it (see e.g., Williams & McKee 1997). However, most of this energy will of course be radiated away.

8.2. AGN:

If the clouds in the ISM have a direct view of the active nucleus, then the integrated energy input (assuming \( \Delta t \leq \) the lifetime of the AGN) is simply

\[ E_{\text{AGN}} \sim \frac{L_{\text{bol}}}{4\pi R^2} A_{cl} \Delta t \]

\[ \sim 10^{57} L_{12} R_{100}^{-2} f_{\text{abs}} \left( \frac{M_c}{10^5 M_\odot} \right)^{2/3} n_4^{-2/3} \left( \frac{\Delta t}{10^7 \text{yr}} \right) \text{erg} \]  

where \( A_{cl} \) is the projected area of the cloud. Thus the ratio of AGN energy input to cloud binding energy is

\[ \frac{E_{\text{AGN}}}{E_B} \sim 10^6 L_{12} R_{100}^{-2}ystem{f}_{\text{abs}} \left( \frac{M_c}{10^5 M_\odot} \right)^{-1} n_4^{-1} \left( \frac{\Delta t}{10^7 \text{yr}} \right) \]  

(40)
which is several orders of magnitude larger than the energy input calculated above for a starburst. (Since the bolometric luminosities are the same in both cases, the same amount of radiation – mostly re-radiated in the far-IR – must of course be incident on a typical cloud in a starburst-powered ULIRG. Precisely because this radiation is dominantly at infrared wavelengths, however, it will have far less impact on the ISM in a ULIRG than the radiation from an AGN, serving mostly to increase the typical ISM temperatures.) Evaporation and ablation of clouds which are exposed to the AGN can be very significant, leading to destruction of the molecular ISM (Begelman 1985).

Because of the large gas column densities inferred in the nuclei of ULIRGs, however, it is likely that most of the ISM does not have an unobscured view of the AGN. Here the fact that the spectrum of an AGN extends to high energies ($E \sim 100$ keV) is of great importance, as these photons can penetrate large column densities before being absorbed. This means that the amount of energy deposited by X-rays can be very large even if there is a significant column between a cloud and the radiation source: the energy deposition rate per unit volume is approximately

$$nH_x \sim 3 \times 10^{-17} \left(\frac{f_x}{0.1}\right) L_{12} R_{100}^{-2} \left(\frac{N_{\text{att}}}{10^{22} \text{ cm}^{-2}}\right)^{-1} n_4 \text{ erg cm}^{-3} \text{ s}^{-1}$$

(Maloney, Hollenbach, & Tielens 1996, hereafter MHT), where $f_x$ is the fraction of the bolometric luminosity emitted in the $1 - 100$ keV energy band, and $N_{\text{att}}$ is the column density of neutral hydrogen between the cloud and the AGN. For shielding columns $N_{\text{att}} \gtrsim 10^{22}$, only hard X-ray ($E > 1$ keV) photons will be present. Unlike the case of the photodissociation regions (PDRs) powered by stellar UV photons, where dust absorption leads to exponential attenuation of the heating and ionization rates with depth, the XDRs powered by AGN are characterized by an only linear decrease of the energy input with increasing column density (the exact scaling with column density depends weakly on the spectral index of the incident radiation field: MHT). The total energy input to the cloud is then

$$E_{\text{AGN}}^x \sim 10^{55} \left(\frac{f_x}{0.1}\right) L_{12} R_{100}^{-2} N_{22}^{-1} \left(\frac{M_c}{10^5 \text{ M}_\odot}\right) \left(\frac{\Delta t}{10^7 \text{ yr}}\right)^2 \text{ erg}$$

(42)

where the shielding column has been scaled to $N_{\text{att}} = 10^{22} N_{22} \text{ cm}^{-2}$. Compared to the cloud binding energy,

$$\frac{E_{\text{AGN}}^x}{E_B} \sim 10^{5} \left(\frac{f_x}{0.1}\right) L_{12} R_{100}^{-2} N_{22}^{-1} \left(\frac{10^5 M_\odot}{M_c}\right)^{2/3} n_4^{-1/3} \left(\frac{\Delta t}{10^7 \text{ yr}}\right) \text{ erg.}$$

(43)

Thus, even if the shielding column between the X-ray source and a cloud is $N_{\text{att}} \sim 10^{24} \text{ cm}^{-2}$, the X-rays from the AGN can still dump $\sim 10^3$ times
the cloud binding energy into a cloud over its lifetime. As in the case of a starburst-powered ULIRG, most of this energy is simply radiated away (although photoevaporation will occur if the clouds are heated enough to raise the sound speed above the escape speed). It does mean, however, that it is extremely easy to “light up” the interstellar medium in a ULIRG, simply in consequence of the energy input rate, whether it is powered by an AGN or a starburst.

9. X-Ray Irradiation in AGN-Powered ULIRGs

As alluded to above, the large column densities which hard X-ray photons can traverse before being absorbed, combined with the large energy per photon, allow X-ray luminous AGN to have a profound impact on the physical and chemical state of the ISM in AGN-powered ULIRGs. In this section I sketch briefly some of the results and their observational consequences.

9.1. PHYSICAL AND CHEMICAL STRUCTURE

Detailed models of the physics and chemistry of XDRs have been discussed by MHT. The important parameter is $H_x$, the X-ray energy deposition rate per hydrogen nucleus. The heating rate (as noted earlier) and the molecule destruction rates scale as $nH_x$, whereas the cooling and molecule formation rates are generally $\propto n^2$; thus the physical and chemical state scales approximately with $H_x/n$. It is convenient to express this in terms of an X-ray ionization parameter (the ratio of photon flux to gas density),

$$\xi = \frac{L_x}{nR^2} = \frac{4\pi F_x}{n}$$

where $F_x$ is the X-ray flux incident on the face of the cloud. For optically thin gas, the ionization parameter determines the physical state (e.g., Tarter, Tucker & Salpeter 1969). In the case of interest here, where the clouds are optically thick to the X-rays (up to some maximum energy), the physical conditions depend on an effective ionization parameter,

$$\xi_{\text{eff}} = \frac{4\pi F_x}{nN_{\alpha}^{\text{att}}} \approx 0.1 \frac{L_{44}}{n_4 R_{100}^2 N_{22}^\alpha}$$

where the $1 - 100$ keV X-ray luminosity is $L_x = 10^{44}L_{44}$ erg s$^{-1}$ and, as noted earlier, the scaling index $\alpha \sim 1$ for typical AGN spectral indices. This effective ionization parameter is directly proportional to $H_x/n$, with $H_x/n \sim 4 \times 10^{-25}\xi_{\text{eff}}$ erg cm$^3$ s$^{-1}$.

Figure 1 shows the physical and chemical structure of an XDR as a function of $\xi_{\text{eff}}$ or, equivalently, distance from the X-ray source. This calculation assumes $L_x = 4 \times 10^{44}$ erg s$^{-1}$, or $f_x \approx 0.1$ for $L_{\text{bol}} = 10^{12} L_\odot$. 


The gas density is constant at \( n = 10^5 \) cm\(^{-3}\), and the column between the X-ray source and the gas is \( N_{\text{att}} = 10^{22} \) cm\(^{-2}\). (Cloud column densities \( N_{\text{cl}} = 2 \times 10^{22} \) cm\(^{-2}\) and linewidths \( \Delta V = 5 \) km s\(^{-1}\) have been assumed in calculating the cooling of optically thick species.) Close to the X-ray source, the gas is warm, \( T \sim 10^4 \) K, atomic, and weakly ionized, with ionization fraction \( x_e \sim 0.01 - 0.1 \). With increasing distance (or increasing column to the X-ray source) the temperature and ionization fraction decreases and the abundances of molecular species increase; at the lowest values of \( \xi_{\text{eff}} \), the temperature has dropped to \( T \approx 25 \) K, and nearly all of the gas-phase carbon is in CO. Atomic oxygen is abundant over the entire range of \( \xi_{\text{eff}} \).

9.2. MOLECULAR SURVIVAL

Figure 1 shows that, for a gas density \( n = 10^5 \) cm\(^{-3}\), CO only becomes an abundant species for \( R \gtrsim 100 \) pc, whereas many ULIRGs show bright CO...
emission on smaller spatial scales. What densities are needed for gas to be molecular in an AGN-powered ULIRG?

Define the fractional abundance of a species by $x_i = n_i/n$, where $n_i$ is the number density of species $i$ and $n$ is the total density of hydrogen nuclei, $n = n_H + 2n_{H_2}$; note that this definition means that the molecular hydrogen fraction $x_{H_2} = 0.5$ if all of the hydrogen is in molecular form. In table 1, I give the density $n_m$ required in order for the CO abundance $x_{CO} = 10^{-4}$ for three different distances, $R = 10$, 100, and 1000 pc from the nucleus, and three different values of the shielding column, $N_{att} = 10^{22}$, $10^{23}$, and $10^{24}$ cm$^{-2}$. Also listed in the table are the corresponding molecular hydrogen fraction $x_{H_2}$ and the gas temperature $T$.

| $N_{att}$ | $n_m$    | $x_{H_2}$ | $T$(K) |
|----------|----------|-----------|--------|
| $R = 10$ pc |
| $10^{22}$ | $1.5 \times 10^6$ | 0.07 | 903 |
| $10^{23}$ | $2.5 \times 10^7$ | 0.10 | 694 |
| $10^{24}$ | $4.8 \times 10^6$ | 0.13 | 545 |
| $R = 100$ pc |
| $10^{22}$ | $1.9 \times 10^6$ | 0.14 | 409 |
| $10^{23}$ | $3.3 \times 10^7$ | 0.19 | 233 |
| $10^{24}$ | $8.5 \times 10^4$ | 0.27 | 146 |
| $R = 1000$ pc |
| $10^{22}$ | $3.7 \times 10^4$ | 0.30 | 125 |
| $10^{23}$ | $4.5 \times 10^4$ | 0.47 | 74 |
| $10^{24}$ | $1.4 \times 10^4$ | 0.48 | 42 |

Table 1 clearly demonstrates how powerful the effect of an X-ray luminous AGN on the ISM can be. At a distance of 100 pc from the nucleus, even with a column of $N_{att} = 10^{24}$ cm$^{-2}$ in front of the X-ray source, the gas density must be $n \gtrsim$ a few $\times 10^4$ cm$^{-3}$ in order for CO to be abundant: for a density $n = 2 \times 10^4$, the CO abundance $x_{CO} < 10^{-6}$. The temperatures are considerably higher than the typical ISM in the Milky Way; note also that the thermal balance has been calculated including only the heating due to X-rays. Clearly, high gas densities are mandatory for molecular survival in AGN-powered ULIRGs, even when the AGN is buried beneath a large column density of gas and dust.
10. Far-Infrared Fine-Structure Lines

In the post-ISO era, surely no one needs to be reminded of the wealth of information provided by far-infrared fine-structure line observations, a point that was made repeatedly throughout this meeting. As discussed by MHT, XDRs are copious sources of emission in these lines.

Figure 2 shows the emergent surface brightnesses in a number of important mid- and far-infrared lines, for the same XDR model parameters as used for Figure 1. Also plotted is the total far-infrared continuum surface brightness from grain emission. Of particular note are: (1) the extremely high line surface brightnesses which can be produced; (2) major cooling lines such as [O I] 63µm and [Si II] 35µm are bright over nearly the entire parameter space; and (3) compared with the far-IR continuum produced in the XDR, the surface brightnesses in these same lines can be extraordinarily high, with line-to-continuum ratios approaching 10%. In contrast, the line-to-continuum ratios produced in PDRs are usually of order 0.1%, and rarely exceed 1% (e.g., Tielens & Hollenbach 1985). This difference is a reflection of the fact that in PDRs the gas heating is limited by the grain photoelectric heating efficiency; in contrast, in XDRs about as much energy is deposited into the gas as into the grains, so that major cooling transitions can carry a large fraction of the total deposited energy (see MHT for details). The other important point to note is that all of these lines arise from neutral or singly-ionized species; because of the large column densities which X-ray photons can traverse, the volume of the XDR can be vastly larger than the volume of any high-ionization region produced by the AGN.

10.1. PARTICULARLY INTERESTING LINES

A number of other infrared transitions are of particular interest for ULIRGs. The near-infrared vibration-rotation lines of molecular hydrogen have been detected from a number of ULIRGs (most spectacularly in the not-quite-ULIRG NGC 6240); the 1.64µm fine-structure line of [FeII] is frequently detected as well. Observations with ISO have produced detections of the [NeII] 12.8µm line in a number of ULIRGs as well, and the first extragalactic detections of the pure rotational transitions of H$_2$, including observations of the archetypical ULIRG Arp 220 (Sturm et al. 1996).

In Figure 3 I have plotted the emergent surface brightnesses for the $v = 1 - 0$ and $v = 2 - 1$ S(1) lines of molecular hydrogen, the 1.64µm [FeII] line, Brγ, and the [NeII] 12.8µm line. As in Figure 2, the high line surface brightnesses are striking. The extent of the [Fe II] emission is limited by gas temperature, since the upper state lies $E/k \sim 10^4$ K above the ground state. The drop-off in molecular hydrogen emission at log $\xi_{\text{eff}} \approx 2$ is also due to declining $T$ (the $v = 1$ and $v = 2$ levels lie approximately 6000 and
12,000 K above ground, respectively); the secondary rise is due to direct nonthermal excitations of the levels. For a fixed density, the [FeII] emission always lies interior to the molecular hydrogen emission (see also Maloney 1997). The run of density with $\xi_{\text{eff}}$ (or radius) will determine the ratios of the $H_2$ and [Fe II] lines with respect to each other and to Br$\gamma$.

An additional interesting result is the intensity of the [Ne II] 12.8$\mu$m line. This is the single most important coolant over a substantial fraction of the plotted parameter space; as much as $\sim 15\%$ of the deposited X-ray energy emerges in this line alone. The resulting surface brightnesses are extraordinarily high, and the total line luminosity can be a substantial fraction of the total hard X-ray luminosity.

The pure rotation lines of molecular hydrogen are of particular interest because they are much less subject to extinction than the near-infrared lines, and because they provide a tracer of warm (few hundred K) molecular gas, unlike the vibration-rotation bands which require $T \gtrsim 2000$ K for...
Figure 3. Emergent surface brightnesses in several important near- and mid-infrared lines for the XDR model of Figure 1.

effective excitation. The S(0), S(1), S(3), and S(5) lines have been detected in NGC 1068 (Lutz et al. 1997) and the S(1) and S(5) lines (at 17 and 6.9 µm, respectively) have been detected in Arp 220 (Sturm et al. 1996).

In Figure 4 I have plotted the surface brightnesses of the S(0), S(1), S(3), and S(5) lines for the XDR model of Figure 1. Current observations lack the spatial resolution to do more than measure the total line luminosities. However, even this should prove extremely useful for constraining models of the ISM in ULIRGs, and XDR models in particular (Lutz et al. 1997).

10.2. THE HCN/CO RATIO

In ULIRGs, the ratio of the HCN \( J = 1 \rightarrow 0 \) line to that of CO is typically \( \sim 0.2 \) (Solomon, Downes, & Radford 1992), an order of magnitude larger than the value typically observed in normal spirals. In the nuclear \( (R \lesssim 100 \text{ pc}) \) region of NGC 1068, this ratio reaches unity (Tacconi et al. 1994). Such high
values have been interpreted as meaning that the density is high \((n \gtrsim 10^5 \text{ cm}^{-3})\), so that both the HCN and CO lines are approximately thermalized, and that both of the transitions are optically thick, or nearly so. However, the inferred high densities must be regarded with some caution, as the HCN rotational transitions can be pumped through a bending mode via absorption at 14\(\mu\)m; this process is plausibly important in both starbursts and AGN (Aalto et al. 1995; Barvainis et al. 1997).

The line center optical depth for a transition at frequency \(\nu\) is

\[
\tau_o = \frac{c^2}{8\pi \nu^3} A_{ji} g_j N_i g_i \Delta V \left(1 - e^{-h\nu/kT_{ex}}\right)
\]

where \(A_{ji}\) is the Einstein \(A\)–coefficient, \(j\) and \(i\) denote the upper and lower states, the \(g\)s are the statistical weights, \(N_i\) is the column density in the lower state, \(\Delta V\) is the linewidth, and \(T_{ex}\) is the excitation temperature characterizing the relative populations of levels \(i\) and \(j\). Assuming equal

Figure 4. Emergent surface brightnesses in the S(0), S(1), S(3) and S(5) pure rotation lines of \(\text{H}_2\), for the XDR model of Figure 1.
excitation temperatures for the two transitions and that $h\nu/kT_{ex} \ll 1$, the ratio of $\tau_o = 1$ columns for the $J = 1 \rightarrow 0$ transitions is then

$$\frac{N_o(\text{HCN})}{N_o(\text{CO})} = \frac{|\mu_{\text{CO}}|^2\nu_{\text{CO}}}{|\mu_{\text{HCN}}|^2\nu_{\text{HCN}}} \simeq 1.8 \times 10^{-3}. \quad (47)$$

This ratio is much less than unity because the $A$–coefficient for the HCN transition is so much larger than for the corresponding transition of CO, in consequence of its much larger dipole moment $\mu$. Thus, if the HCN abundance is more than a fraction of a percent of the CO abundance, the HCN $J = 1 \rightarrow 0$ transition will be optically thick if the CO transition is. Of course, if the CO $J = 1 \rightarrow 0$ optical depth is very large, then a much smaller HCN abundance will still lead to an optically thick HCN line. Furthermore, it is very important to note that equation (47) gives the ratio of required column densities in $J = 0$. Because of its much lower critical density, it is likely that the partition function for CO will be close to the LTE limit for the relevant conditions, while that of HCN will not, so that the CO molecules will be distributed over a much larger number of rotational states. Hence the ratio $N_o/N_{\text{tot}}$ will be much larger for HCN than for CO, also reducing the required HCN abundance.

In the quiescent interstellar medium in the solar neighborhood, the optical thickness condition is not fulfilled, as the HCN abundance is usually $x_{\text{HCN}} \sim 10^{-4} x_{\text{CO}}$. Furthermore, there are indications that in very active galactic nuclei (either high SFR or AGN), the optical depths in the CO lines are only modest (Aalto et al. 1995; Barvainis et al. 1997), so that the HCN lines are not optically thick in reflection of very optically thick CO lines. However, the increased ionization rate in an XDR can lead to an enhanced abundance of HCN relative to CO (Lepp & Dalgarno 1996). In Figure 5 I show the abundances of CO, HCN, and the ratio $x_{\text{HCN}}/x_{\text{CO}}$ as a function of $\xi_{\text{eff}}$ and distance. The AGN parameters are the same as previously, but I have increased the density to $n = 10^8$ cm$^{-3}$ simply to make the gas dominantly molecular within 100 pc of the nucleus. The HCN/CO ratio is greater than $10^{-3}$ over about a factor of three in radius. Thus in an XDR the HCN abundance can be elevated sufficiently relative to CO to explain the observed line ratios. (In hot star-forming cores, the HCN/CO ratio also reaches values of order $10^{-3}$ [Blake et al. 1987], so elevated values may be expected in starburst-powered ULIRGs as well.)

11. PAH Emission

The mid-IR emission features attributed to polycyclic aromatic hydrocarbons (PAHs) have been used to discriminate between AGN and starbursts in ULIRGs (e.g., Lutz et al. 1998), based on the observation that these fea-
Figure 5. HCN and CO abundances and their ratio as a function of $\xi_{\text{eff}}$. The assumed AGN and cloud parameters are the same as Figure 1, except that the assumed density has been increased to $n = 10^8 \text{ cm}^{-3}$.

Features are weak or absent in classical AGN but generally strong in starbursts. Does the presence of PAH features imply the absence of an AGN?

Voit (1992) has investigated the effects of X-ray irradiation on PAHs. Absorption of an energetic photon leads to destruction of the PAH, through two processes: (1) photo-thermal dissociation (i.e., evaporation), and (2) Coulomb “explosion”, in which the PAH is doubly ionized by the incident photon and subsequently fragments as the repulsive Coulomb force effectively reduces the binding energy of the PAH. To estimate the magnitude of the destruction timescale, assume that every absorption of an X-ray photon by a PAH leads to its destruction$^1$:

$$\tau_{\text{xd}} \sim 2 \left( \frac{f_x}{0.1} \right) L_{12} R_{100}^{-2} N_{22}^{1.6} \text{ yr}$$  \hspace{1cm} (48)

$^1$This is likely to overestimate the PAH destruction rate; far more laboratory work (e.g., Jochims et al. 1996) needs to be done in this area.
assuming a flat ($\nu L_\nu = \text{constant}$) spectrum. Even if $N_{\text{att}} = 10^{24}$ cm$^{-2}$, the PAH X-ray destruction time is only $\tau_{\text{xd}} \sim 3000$ years at 100 pc.

To determine whether PAHs can survive in the face of such short destruction timescales, we need to compare $\tau_{\text{xd}}$ with the rate at which the PAHs re-accrete material (this is dominated by accretion of C$^+$ if the PAHs are neutral). Since a photo-destruction rate is balanced against a density-dependent reaction rate, this again leads to a critical ionization parameter at which $\tau_{\text{xd}} = \tau_{\text{acc}}$, which, using the results of Voit (1992), is

$$U_{\text{cr}} \equiv \frac{n_{\text{ph}}}{n_H} \sim 5 \times 10^{-9} \left(\frac{Y}{0.3}\right) N_{50}^{1/2} f_{\text{PAH}} \frac{1}{\Sigma(N_H)}$$ \hspace{1cm} (49)

where $Y$ is an effective sticking coefficient for accretion, the number of carbon atoms in the PAH is $N_C = 50 N_{50}$, and $f_{\text{PAH}}$ is the fraction of PAHs which are neutral. $\Sigma(N_H)$ is a dimensionless, spectrum-weighted cross section for photodissociation of carbon from a PAH, (i.e., the photon flux-weighted photodissociation cross-section, normalized to the PAH geometric cross-section), approximately given by $\Sigma(N_H) \sim 4 \times 10^{-5}/N_{22}$ (see Figure 3 in Voit 1992). This gives the critical ionization parameter for PAH survival as

$$U_{\text{cr}} \sim 1.3 \times 10^{-4} \left(\frac{Y}{0.3}\right) N_{50}^{1/2} f_{\text{PAH}} f_{C^+} N_{22}$$ \hspace{1cm} (50)

where $f_{C^+} = x_{C^+}/x_C$(total). From this expression, we find that PAHs will survive against X-ray destruction at a radius (with $f_{C^+} = f_{\text{PAH}} = 1$)

$$R_{\text{cr}} \sim 100 \left[\left(\frac{L_{12}}{0.1}\right) \left(\frac{T}{100 \text{ K}}\right)\right]^{1/2} \left(\frac{\dot{P}_{\text{ISM}}}{10^7 \text{ cm}^{-3} \text{ K}}\right)^{-1/2} N_{22}^{-1/2} \text{ pc.}$$ \hspace{1cm} (51)

Note the importance of large ($N_{22} \gtrsim 1$) shielding columns and high pressures for the survival of PAHs. Since, as we have seen, both large column densities and high pressures are characteristic of the ISM in ULIRGs, it is quite probable that PAHs will in general resist destruction by X-ray irradiation even in AGN-powered ULIRGs, and so the presence of PAH features should not be taken as conclusive proof of the absence of an AGN.

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