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Nuclear starbursts and AGN fueling

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Abstract. We argue that radiation pressure from star formation can support a galactic disk against its own self-gravity. This model is appropriate when the disk is optically thick to its own infrared radiation, as in the central regions of Ultraluminous Infrared Galaxies and in the outer parts of accretion disks in Active Galactic Nuclei. We review the properties of radiation-pressure supported disks and discuss the conditions under which AGN can be fueled by gas stored in an outer starburst disk.

1. Introduction

Star formation in galaxies is observed to be globally inefficient; in a sample of local spiral galaxies and luminous starbursts, Kennicutt (1998) showed that only a few percent of the gas is converted into stars each dynamical time. This inefficiency may result from "feedback": the energy and momentum injected into the interstellar medium (ISM) by star formation can in turn regulate the star formation rate in a galaxy. Models for feedback in the ISM generally invoke energy and momentum injection by supernovae and stellar winds (e.g., McKee & Ostriker 1977). However, the momentum supplied to the ISM by the radiation from massive stars is comparable to that supplied by supernovae and stellar winds. The UV radiation from massive stars is absorbed and scattered by dust grains, which reprocess the UV emission into the IR. Because the dust grains are hydrodynamically coupled to the gas, radiation pressure on dust can help stabilize the gas against its own self-gravity and may therefore be an important feedback mechanism.

When the ISM of a galaxy is optically thick to the re-radiated IR emission, radiative diffusion ensures that all of the momentum from the photons produced by star formation is efficiently coupled to the gas. In this review, we argue that this limit is applicable on scales of hundreds of parsecs in luminous gas-rich starbursts, including Ultraluminous Infrared Galaxies (ULIRGs), the most luminous and dust enshrouded starbursts known. In addition, the outer parts of disks around active galactic nuclei (AGN) are expected to be dominated by radiation pressure on dust (e.g., Sirko & Goodman 2003). In fact, there is probably not a clear distinction between the galactic disk and the AGN disk: if luminous AGN are fueled by gas from the cold ISM of their host galaxy, there must be a continuous transition from the star-forming "galactic" disk to the central black hole's "accretion disk." The nature of this transition, and indeed whether it occurs at all, remains uncertain. The problem is that the outer parts of AGN disks are strongly self-gravitating with a Toomre stability parameter $Q \ll 1$ (Shlosman & Begelman 1989; Shlosman, Begelman, & Frank 1990; Goodman 2003). It is difficult to see how the disk avoids fragmenting almost entirely into stars. One possibility is that in the dense gas-rich nuclear regions of galaxies, angular momentum transport proceeds via global torques (e.g., bars, spiral waves, large-scale magnetic stresses, etc.), rather than a local viscosity (Shlosman, Frank, & Begelman 1990; Goodman 2003). In this case, gas may inflow sufficiently rapidly to avoid turning entirely into stars. At the end of this review, we briefly discuss the connection between galactic-scale star-forming disks and smaller-scale AGN disks.

The plan for the rest of this paper is as follows. In §2, we discuss a simple model of self-regulated star formation in galactic disks. We focus on disks that are optically thick to their own IR radiation. In §3, we then briefly discuss how the results of §2 can be extended to include angular momentum transport and thus address the problem of AGN fueling. This review draws heavily on Thompson, Quataert, & Murray (2005), hereafter TQM.

2. Self-regulated Star-Forming Disks

We consider a galactic disk in radial centrifugal balance with a rotation rate $\Omega = \Omega_K$, where $\Omega_K = \sqrt{2}\sigma/r$ is the Keplerian angular frequency in an isothermal potential with velocity dispersion σ. The total surface density at radius r is given by

$$\Sigma_{\rm tot} = \frac{\sigma^2}{\pi G r} \sim 0.6\,\sigma_{200}^2\, r_{\rm kpc}^{-1}\ {\rm g\ cm^{-2}}, \qquad (1)$$

where $\sigma_{200} = \sigma/200$ km s^{-1} and the radial scale is in units of kpc. For simplicity, we assume that the underlying potential is spherical, as would be provided by a stellar bulge or the galaxy's dark matter halo. We further assume that the gas mass is a constant fraction $f_g = M_g/M_{\rm tot} = \Sigma_g/\Sigma_{\rm tot}$ of the total dynamical mass, where Σ_g is the gas surface density. For a thin disk vertical hydrostatic equilibrium implies $h \approx c_s/\Omega$ where $c_s^2 = p/\rho$ is the sound speed and h is the pressure scale height.

We assume that star formation in the disk is governed by local gravitational instability as described by Toomre's Q-parameter (Toomre 1964). In particular, we argue that the star formation rate per unit area $\dot{\Sigma}_\star$ adjusts so that

$$Q = \frac{\kappa_\Omega c_s}{\pi G \Sigma_g} = \frac{\Omega^2}{\sqrt{2}\pi G \rho}, \qquad (2)$$

is maintained close to unity. In equation (2), $\kappa_\Omega^2 = 4\Omega^2 + d\Omega^2/d\ln r$ is the epicyclic frequency. The hypothesis of marginal Toomre stability has been discussed extensively in the literature (e.g., Paczynski 1978; Gammie 2001; Goodman & Sirko 2003) and is based on the idea that if $Q \gg 1$ then the disk will cool rapidly and form stars, while if $Q \ll 1$ then the star formation will be so efficient that the disk will heat up to $Q \sim 1$. There is evidence for $Q \sim 1$ in the Milky Way (e.g., Binney & Tremaine 1987), local spiral galaxies (e.g., Martin & Kennicutt 2001), and starbursts such as ULIRGs (e.g., Downes & Solomon 1998). From equation (2) it follows that the density distribution of the gas is determined solely by the local Keplerian frequency:

$$n \sim 170\sigma_{200}^2 r_{\rm kpc}^{-2} Q^{-1}\ {\rm cm^{-3}}. \qquad (3)$$

2.1. The Case for Radiation Pressure

The nuclei of gas-rich starbursts are optically thick to their own infrared radiation. Radiative diffusion then ensures that radiation pressure provides the dominant vertical support against gravity. In this section we describe disk models appropriate to this limit. The vertical optical depth of the disk is given by $\tau_V = \Sigma_g \kappa/2$, where κ is the Rosseland mean opacity to dust. Evaluating this expression yields

$$\tau_V = \frac{\kappa\sigma^2 f_g}{2\pi G r} \sim 0.15\sigma_{200}^2 f_{g\,0.5} r_{\rm kpc}^{-1} \kappa_1. \qquad (4)$$

The radius at which $\tau_V = 1$ is then

$$R_{\tau_V=1} = \frac{\kappa\sigma^2 f_g}{2\pi G} \simeq 150\kappa_1\sigma_{200}^2 f_{g\,0.5}\ {\rm pc} \qquad (5)$$

and thus for the largest most gas-rich starbursts ($\sigma \sim 300$ km s^{-1} and $f_g \sim 1$) the inner ~ 700 pc are optically thick.

In the optically thick limit, the flux and effective temperature from the disk are given by

$$\sigma_{\rm SB} T_{\rm eff}^4 = \frac{1}{2}\epsilon\dot{\Sigma}_\star c^2, \tag{6}$$

where ϵ is the efficiency with which star formation converts mass into radiation ($\epsilon \sim 10^{-3}$ for a Salpeter IMF from $1 - 100\,M_\odot$) and the factor of $1/2$ arises because both the top and bottom surfaces of the disk radiate. The midplane temperature is related to the effective temperature by $T^4 \approx (3/4)\tau_{\rm V} T_{\rm eff}^4$, where the opacity $\kappa(T,\rho)$ in $\tau_{\rm V}$ should be evaluated using the central temperature and mass density of the disk. The temperature dependence of the opacity is important for this problem and is discussed shortly. For $\tau_{\rm V} \gtrsim 1$, the radiation pressure is given by

$$p_{\rm rad} = \frac{4\sigma_{\rm SB}}{3c}T^4 = \frac{\sigma_{\rm SB}}{c}\tau_{\rm V} T_{\rm eff}^4 = \frac{1}{2}\tau_{\rm V}\epsilon\dot{\Sigma}_\star c. \tag{7}$$

In addition to radiation pressure, supernovae explosions deposit momentum into the ISM via swept-up shells of cold gas. From Thornton et al. (1998) we estimate that each supernova has an asymptotic momentum of $3\times 10^{43} E_{51}^{13/14} n_1^{-1/4}$ g cm s^{-1}, where $E_{51} = E/10^{51}$ ergs is the initial energy of the supernova and $n_1 = n/1\,{\rm cm}^{-3}$ is the density of the ambient medium. The effective pressure of the cold ISM from supernovae is thus

$$p_{\rm sn} \sim 1.5\times 10^8 n_1^{-1/4} E_{51}^{13/14}\,\dot{\Sigma}_\star \equiv \xi\epsilon\dot{\Sigma}_\star c \tag{8}$$

where $\xi \sim 5 n_1^{-1/4} E_{51}^{13/14}$ measures the momentum injected by supernovae relative to that injected by radiation from massive stars (stellar winds supply an amount of momentum comparable to that of supernovae). For the dense nuclei of starburst galaxies where supernova remnants are highly radiative, we expect $\xi \sim 1$.

Comparing equations (8) and (7) shows that radiation pressure exceeds the turbulent pressure due to supernovae by a factor of $\sim \tau_{\rm V}$ (assuming $\xi \sim 1$). Radiation pressure support will thus dominate the vertical support of compact optically-thick starbursts.

With equation (7) it is straightforward to solve for the physical parameters of the model galactic disk, T, $T_{\rm eff}$, $\dot{\Sigma}_\star$, etc. in terms of our model variables: σ, f_g, ϵ, and the radius in the disk r. The details of these solutions are given in TQM. Here we highlight several of the main results.

The observable properties of the disk depend sensitively on the magnitude of the opacity. In particular, the star formation rate per unit area is proportional to $\Sigma_g^2/\tau_{\rm V} \sim \Sigma_g/\kappa$. This follows from setting the radiation pressure in equation (7) equal to the pressure required from hydrostatic equilibrium, $\sim \pi G\Sigma_g^2$. This expression is essentially the Eddington limit, i.e., in a radiation pressure supported disk each annulus radiates at its local Eddington limit with the flux determined in large part by the opacity. Therefore, in regions of the disk where the opacity is low, there must be more star formation to maintain $Q \sim 1$. Conversely, where the optical depth is high, less star formation is required.

At the temperatures of interest on scales of $\sim 1 - 100$ pc in galactic nuclei, the dominant opacity is due to dust. For temperatures $T \lesssim 100 - 200$ K, the opacity is essentially independent of density and can be approximated by $\kappa = \kappa_0 T^2$, with $\kappa_0 \simeq 2.4\times 10^{-4}$ cm^2 g^{-1} K^{-2}. The scaling of κ with T^2 follows from the fact that the dust absorption cross section scales as $\lambda^{-\delta}$ with $\delta \to 2$ in the Rayleigh limit. The normalization κ_0 is somewhat uncertain and depends on grain physics and the dust-to-gas ratio; the latter may vary systematically as a function of radius and metallicity in starburst disks. In what follows we set $\kappa_{-3.6} = \kappa_0/2.4\times 10^{-4}$ cm^2 g^{-1} K^{-2} and retain the scaling with κ_0.

Remarkably, because $T \propto \Sigma_g^{1/2}$ from hydrostatic equilibrium and $\dot{\Sigma}_\star \propto \Sigma_g/\kappa$ if the disk is radiation pressure supported, with $\kappa \propto T^2$ we find that the star formation rate per unit area, the effective temperature, and flux are all independent of virtually all model parameters:

$$\dot{\Sigma}_\star \sim 10^3\,\epsilon_3^{-1}\kappa_{-3.6}^{-1} Q^{1/2}\ {\rm M_\odot\,yr^{-1}\,kpc^{-2}} \tag{9}$$

$$F \sim 10^{13}\,\kappa_{-3.6}^{-1} Q^{1/2}\ {\rm L_\odot\,kpc^{-2}}, \tag{10}$$

and

$$T_{\rm eff} \sim 88\,\kappa_{-3.6}^{-1/4} Q^{1/8}\ {\rm K}. \tag{11}$$

In particular, note that neither $\dot{\Sigma}_\star$, F, nor $T_{\rm eff}$ depend on r, σ, or f_g. Our model thus predicts that starburst disks have roughly constant flux and effective temperature over a range of radii.

The constancy of these disk observables follows from three ingredients: (1) the disk is supported by radiation pressure and $\tau_V \gtrsim 1$, (2) the disk self-regulates with $Q \sim 1$, and (3) $\kappa \propto T^2$ at low T. Above $T \sim 100 - 200$ K, κ ceases to increase monotonically with T and equations (9)-(11) no longer hold. The temperature exceeds ~ 200 K at a radius $R_{200} \sim 40\sigma_{200}^2 f_{g\,0.5} T_{200}^{-2} Q^{1/2}$ pc. This radius should be compared with the radius at which $\tau_V = 1$. Using the $\kappa \propto T^2$ scaling, we find that

$$R_{\tau_V=1} \sim 250\sigma_{200}^2 f_{g\,0.5}\kappa_{-3.6}^{1/2} Q^{1/4} {\rm pc}. \tag{12}$$

Therefore, we expect $\dot{\Sigma}_\star$, $T_{\rm eff}$, and F to be roughly constant in the radial range $R_{200} \lesssim r \lesssim R_{\tau_V=1}$, $\sim$ hundreds of parsecs for fiducial parameters.

2.2. Application to ULIRGs

In this section we highlight the application of our optically thick disk models to ULIRGs. To focus the discussion, we emphasize the application to Arp 220, a prototypical ULIRG. Arp 220 consists of two merging nuclei separated by about 350 pc (Graham et al. 1990). The total FIR luminosity of the system is $\sim 10^{12} L_\odot$. The $2 - 10$ keV X-ray luminosity is only $\sim 3 \times 10^9 L_\odot$, however, and the column density of X-ray absorbing material must exceed 10^{25} cm^{-2} if an obscured AGN is to contribute significantly to the bolometric luminosity. Thus, there is little evidence for an energetically important AGN. The detection of numerous radio supernovae also supports a starburst origin for most of the radiation from Arp 220 (Smith et al. 1998).

Arp 220 has an extended CO disk with a scale of ~ 500 pc (Downes & Solomon 1998). Perhaps $\sim 1/2$ of the luminosity, however, appears to come from two counter-rotating nuclear disks, each of which is $\sim$ 100 pc in extent (e.g., Soifer et al. 1999; Downes & Solomon 1998). Radio observations also show that nearly all of the radio flux — presumably associated with supernovae and star formation — originates within $\sim 50 - 100$ pc of the double nuclei (Condon et al. 1991). The total mass in each of the compact nuclear disks is $\sim 2 \times 10^9 M_\odot$, with a large gas fraction of $f_g \sim 0.5$ (Downes & Solomon 1998). The nuclear region of Arp 220 is optically thick to at least 25μm and the inferred blackbody temperature at this wavelength is $\gtrsim 85$ K (Soifer et al. 1999). The estimated gas mass and radius of the disk imply a surface density of $\Sigma_g \approx 10$ g cm^{-2}, suggesting that the nuclear region is probably optically thick even in the FIR (as implied by eq. [5]).

In the optically-thick limit, with $\kappa \propto T^2$, our model predicts a radiative flux of $\sim 10^{13}\,{\rm L}_\odot\,{\rm kpc}^{-2}$ (eq. [10]), in good agreement with the flux inferred for the compact nuclei in Arp 220 (see also Fig. 1 discussed below). Our model also predicts an effective temperature of ~ 88 K for this very compact emission (eq. [11]), in agreement with that estimated by Soifer et al. (1999). Lastly, we note that for a gas fraction of $f_g \sim 0.5$ and a velocity dispersion of $\sigma \sim 200$ km s^{-1}, our model predicts a sound speed (i.e., turbulent velocity or linewidth) of $c_s \sim 50$ km s^{-1}, similar to that observed in CO by Downes & Solomon (1998).

In their study of CO emission from ULIRGs, Downes & Solomon (1998) identified compact nuclear starbursts in Mrk 273 and Arp 193 with properties similar to those discussed above for Arp 220. More directly, Condon et al. (1991) imaged the radio emission in the 40 brightest galaxies in the IRAS Bright Galaxy Sample. They resolved the emission in nearly all of the sources (36/40) and found sizes $\sim$ 100 pc. They further showed that the radio emission from ULIRGs – correcting for free-free absorption in some cases – places them on the FIR-radio correlation of starburst galaxies. This is consistent with starbursts contributing significantly to the bolometric power of these sources. In the absence of direct FIR imaging of ULIRGs, the radio sizes from Condon et al. (1991) are currently the best estimate of the size of the nuclear starbursts in these systems. Figure 1 shows a histogram of the number of sources at a given flux inferred using the FIR luminosity and the size of the resolved radio source from Condon et al. (1991). The histogram shows a peak centered on a flux $\sim 10^{13}$ L$_\odot$ kpc^{-2} with a dispersion of a factor of ~ 3. This characteristic 'observed' flux is consistent with the predictions of our optically thick disk models (eq. [10]).

The characteristic flux $\sim 10^{13}$ L$_\odot$ kpc^{-2} found in Figure 1 is equivalent to a blackbody temperature of ~ 90 K (eq. [11]). This is noticeably larger than the typical color temperature of ~ 60 K inferred from the FIR spectra of ULIRGs. Another way to state this result is that using the observed FIR spectra and luminosity, the blackbody size of the FIR emitting region is typically larger (by a factor of few) than the radio sizes observed by Condon et al. (1991). This is likely because the compact nuclei of many ULIRGs are optically thick even at $\sim 30\mu m$, so that radiative diffusion degrades the ~ 90 K emission and ensures that the FIR size can be larger than the true size of the nuclear starburst. This interpretation requires sufficient obscuring gas at large radii, but also that star formation in this gas does not dominate the bolometric power of the source (or else the radio source would be more extended than is observed). In our models we find that if the gas fraction in the nuclear region increases at small radii, as Downes & Solomon (1998) infer for several systems, then most of the luminosity is produced near the radius where $\tau_V \sim 1$, rather than in the extended optically thin portion of the disk at larger radii.

3. AGN Fueling

In the previous section we considered the properties of large-scale starburst disks. In this section we briefly address the problem of AGN fueling by discussing the connection between these disks and sub-parsec scale AGN disks.

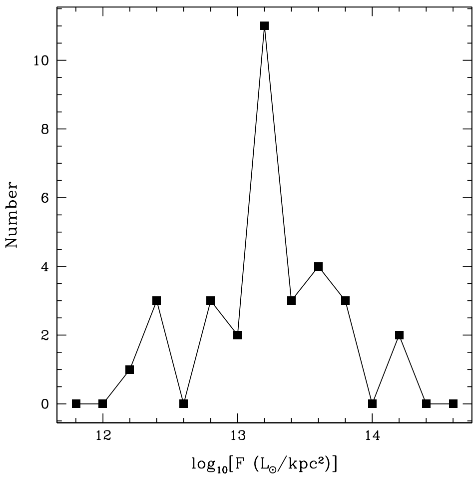

Fig. 1. Histogram of the number of ULIRGs at a given flux using the sample in Tables 1 & 2 of Condon et al. (1991); the bins have a width of 0.2 in $\log_{10}$ F. We estimate the intrinsic flux in the nuclear starburst using $F = L_{\rm FIR}/A_{\rm radio}$, where $A_{\rm radio}$ is the area of Condon et al's elliptical Gaussian fit to the radio emission; we exclude the 4 unresolved sources. The peak in the histogram at $\sim 10^{13}$ L$_\odot$ kpc^{-2} is in good agreement with the predictions of radiation pressure supported disk models.

The gas stored in the outer-scale starburst disk is the likely fuel reservoir for the smaller-scale AGN disk. The rate at which mass flows in towards the AGN can be roughly estimated by considering a Shakura-Sunyaev accretion disk with viscosity $\nu = \alpha c_s h$, in which case the mass accretion rate is given by

$$\dot{M} = 2\pi\nu\Sigma_g \left|\frac{d\ln\Omega}{d\ln r}\right| \sim \frac{\alpha c_s^3}{GQ}. \tag{13}$$

If star formation maintains $Q \sim 1$ at large radii, the resulting random velocity can be shown to be

$$c_s \sim 40\Sigma_g^{1/2} M_9^{1/2} Q \,\mathrm{km\,s^{-1}} \tag{14}$$

where M_9 is the total gas mass in the disk at radius r in units of $10^9\,M_\odot$. Using equation (14) to estimate c_s, equation (13) implies accretion rates of $\dot{M} \sim 10$ M$_\odot$ yr^{-1}, ample to fuel a powerful AGN.

AGN disks do not have $Q \gtrsim 1$ due to accretion heating until radii $\sim 0.01 - 0.1$ pc (Goodman 2003). Thus fragmentation and star formation remains an impediment to accretion down to very small scales. In fact, the problem of AGN fueling becomes progressively more difficult on $\sim$ pc scales. The $\sim$ 100 pc scale starburst disks have a large h/r due to stirring by star formation. This facilitates rapid inflow to small radii, as estimated above. At smaller radii, however, the disk is much thinner and the viscous time becomes much longer, making it more likely that the disk will fragment into stars rather than accreting. To quantify this difficulty, we note that the viscous time in a thin $Q \sim 1$ disk with α viscosity is given by

$$t_{vis} \sim 3000 \frac{M_8}{\alpha^{1/3} \dot{M}_1^{2/3} R_{\rm pc}} \Omega^{-1} \qquad (15)$$

where M_8 is the black hole mass in units of $10^8 M_\odot$, $\dot{M}_1$ is the accretion rate in units of 1 M$_\odot$ yr^{-1}, and we have assumed that the black hole dominates the gravitational potential. In equation (15) we have expressed the viscous time in units of the orbital period Ω^{-1}. Observationally, Keniccutt (1998) has shown that gas in galactic disks typically fragments into stars on a timescale $\sim 50\Omega^{-1}$. Although Kennicutt's observations do not include $\sim$ parsec scale disks relevant for AGN fueling, they do cover a range of $\sim 10^4$ in gas surface density, from normal spiral to luminous starbursts. The comparison between these observations and equation (15) highlights that either star formation on parsec-scales around AGN is $\sim$ 100 times less efficient than is typically observed in galactic disks, or angular momentum transport (gas inflow) must proceed much more rapidly than predicted by a local α model. We suggest that, as in the larger-scale starburst on $\sim$ 100 pc scales discussed in §2.1, radiation pressure from star formation efficiently pressurizes the inter-stellar medium in parsec-scale AGN disks, reducing the star formation efficiency and allowing gas to flow inwards. In addition, it is plausible that in the dense gas-rich nuclear regions of galaxies, angular momentum transport proceeds via global torques (e.g., bars, spiral waves, large-scale magnetic stresses, etc.), rather than a local viscosity (Shlosman, Frank, & Begelman 1990; Goodman 2003). This will also faciliate the inflow of gas towards a central AGN.

4. Conclusions

In this review, we have argued that radiation pressure from star formation can support a galactic disk against its own self-gravity. This model is appropriate when the disk is optically thick to its own infrared radiation, as in the central regions of ULIRGs and the outer parts of accretion disks in AGN. Radiation pressure supported star-forming disks can account for the essential observed properties of ULIRGs (§2.2). In addition, radiation pressure support may help stave off the self-gravity of gas on parsec-scales in AGN, facilitating accretion onto the central black hole.

Although a detailed theoretical understanding of the connection between nuclear starbursts and AGN fueling remains uncertain, it is important to point out that there are an increasing number of observational probes of accretion disks on the parsec scales where self-gravity is the most problematic (e.g., water masers; Maloney 2002) and that there is direct evidence for star formation in the central parsecs of several AGN (e.g., Storchi-Bergmann et al. 2005). In addition, young stellar disks have been discovered in the central ~ 0.1 parsecs of both our Galactic Center (e.g., Genzel et al. 2003) and M31 (Bender et al. 2005). The most natural interpretation is that these stars were formed *in situ* in an accretion disk around the massive black hole (e.g., Levin & Beloborodov 2003; TQM). These observations highlight that star formation does persist very close to a central massive black hole. They further suggest that star formation may play a role in the observed phenomenology of AGN and in determining the dynamics of parsec-scale AGN accretion disks.

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