RevMexAA (Serie de Conferencias), **6**, 235–237 (1997)

DO STARBURSTS HAVE THE POWER TO PRODUCE JETS?

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RESUMEN

El modelo canónico para AGNs establece que la acreción de materia de un disco hacia un agujero negro es la fuente principal de energía de estos objetos. Por otra parte, el modelo de "starburst" para AGNs es adecuado para explicar el espectro de líneas de emisión y del continuo óptico-UV, pero no la producción de radio jets. Aquí investigamos la producción y colimación de flujos en el escenario de los "starburst".

ABSTRACT

The canonical model for AGN establishes that mass accretion from a disk by a supermassive black hole (BH) is the ultimate source of energy in these objects. X-ray observations and the occurrence of collimated jets in some classes of AGNs are considered the most convincing signatures for BH models. On the other hand, the starburst model for AGNs has been proved plausible in explaining the observed emission line spectrum, the UV-optical continuum and related variability, but has failed so far to explain jet production. Here we investigate the production and collimation of outflows in a starburst scenario.

Key words: **ACCRETION DISKS — HYDRODYNAMICS — ISM: JETS AND OUTFLOWS**

1. INTRODUCTION

Recent radio observations of a distance-limited sample of edge-on Seyfert galaxies by Colbert et al. (1996), have shown that 6 of the 10 observed galaxies, have extended radio structures with radial extent between 5 and 30 kpc. They are oriented at skewed angles ($\Delta = 35^\circ - 90^\circ$) with respect to the galaxy minor axis and do not look like the wide-angled winds observed in typical starburst galaxies. Although less collimated and powerful, their morphology resembles the jets observed in extended radio galaxies. Based on the fact that starburst (SB) models (e.g., Terlevich et al. 1992), seem to better suit the phenomena related to the low-level-activity AGN class of Seyfert galaxies, we here examine whether massive nuclear star formation may be present at high enough rates to drive (and collimate) galactic flows out to kpc scales in Seyfert galaxies.

First, in order to build a consistent SB scenario and evaluate its energetics, mass loss, and rate of supernova production, we calculated the evolution of several starburst stellar clusters based on the evolutionary population synthesis models of Schaller et al. (1992). As initial conditions we have assumed a stellar velocity dispersion $v_s = 200$ km s^{-1}; a Salpeter initial IMF with stellar masses in the range $[M_l = 1 - 8\ M_\odot, M_u = 120\ M_\odot]$; initial number of stars $N_c = 10^6 - 4 \times 10^9$ (which corresponds to cluster radius $R_c = 0.2 - 705$ pc); and an energy per supernova $E = 10^{51}$ erg s^{-1}. Also, we have assumed that the system is rotating with an ellipticity $\epsilon = 2.5 \times 10^{-3}$ (Spitzer & Saslaw 1966). The gas released by star formation will cool by free-free emission in time scales much smaller than the evolutionary time scales of the system and will thus fall towards the centre. Due to rotation, it will settle into a disk with initial characteristic radius $R_d = \epsilon^{1/2} R_c$. The disk will eventually become gravitationally unstable and also undergo star formation. As an example, Fig. 1 shows the results for a cluster with 3×10^8 stars.

A strong nuclear starburst can, in principle, drive a wide-angled wind out of the system (see, e.g., Heckman et al. 1990, hereafter HAM). If the outflow is driven by a SB, then the observed non-thermal radio power (P_r) should be correlated with the supernovae production rate (ν_{SN}) by $P_r \simeq 1.3 \times 10^{23} (\nu_{12})^{-\alpha}\, \nu_{SN}$ W Hz^{-1}, where ν_{12} is the radio frequency in 1 GHz, and $\alpha \simeq 0.8$ is the spectral index. Using the observed radio power of the Seyfert outflows, we find $\nu_{SN} \simeq 5.1 \times (10^{-3} - 10^{-1})$ yr^{-1} (see also Colbert et al. 1996 and references therein),

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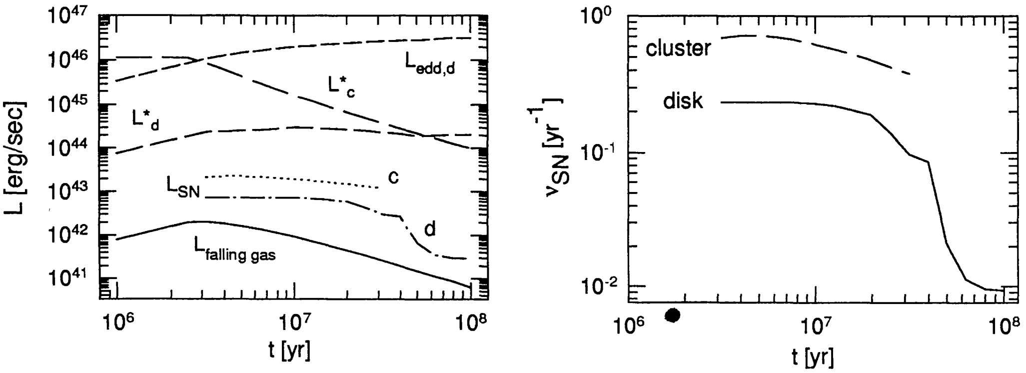

Fig. 1. *a)* Evolution of a stellar cluster and its disk core, with ($M_l = 1\ M_\odot$, $M_u = 120\ M_\odot$); $N_c = 3 \times 10^8$; $R_c = 53$ pc; total cluster mass $M_c = 9.5 \times 10^8 M_\odot$; $R_d = 2.6$ pc; total number of stars in the disk $N_d = 9 \times 10^7$; stellar mass in the disk $M_d = 1.6 \times 10^8 M_\odot$; and gas density in the disk $\rho_d = 9 \times 10^7$ g cm^{-3}. Luminosity sources shown: L_{SN} - total SN luminosity in the cluster and disk; $L_{falling-gas}$ - rate of energy released by the infalling gas in the disk; L^* - starlight in the cluster and disk; and $L_{edd,d}$ - the Eddington luminosity limit in the disk. For a cluster with a mass ten times larger (smaller), all the luminosity values increase (decrease) by an order of magnitude; *b)* Rates of supernovae production, ν_{SN}, in the cluster and the disk.

which is consistent with the expected values of ν_{SN} in the SB models (see Fig. 1*b*). A SB with such ν_{SN} can inject *kinetic* energy into the ambient medium at a rate (HAM) $L_K \simeq 3.5 \times 10^{43} \nu_{SN} \simeq 2 \times (10^{41-43})$ erg s^{-1}, which is comparable to the total SN luminosity in the disk core of our SB models (see Fig. 1*a*).

Now, for the SB to drive a wind, its supernova rate must be high enough to create a cavity of hot gas whose cooling time is much larger than its expansion time scale, and the wind must be sufficiently powerful to blow out of the surrounding atmosphere. The ratio of the cooling to the dynamical sound-crossing time in a SN-driven wind embedded in an exponential atmosphere with a scale height H_{pc} (in pc) is (HAM and references therein)

$$t_{cool}/t_{dyn} = 2.3\, n_{o,8}^{-1.1} L_{K,43}^{0.61} H_{pc}^{-1.7} (\eta/0.1)^{-1.6}\,, \tag{1}$$

where $n_{o,8}$ is the number density in the disk (in 10^8 cm^{-3}), $L_{K,43}$ is in 10^{43} erg s^{-1}, and η is the metal abundance relative to the solar. This relation indicates that the condition for the formation of the hot cavity ($t_{cool} > t_{dyn}$) is just marginally satisfied if the density in the starbursting disk is $\lesssim 10^8$ cm^{-3} and/or the metal abundance $\eta < 0.1$. We note, however, that a decrease of n_o in the SB model, implies a decrease of the SN luminosity and thus of L_K, so that n_o cannot be either much smaller than 10^8 cm^{-3}.

The condition that L_K produce a wind which is powerful enough to blow out of the exponential atmosphere is provided by

$$L_{K,43} > 5\, n_{o,8}^{-1/2} H_{pc}^2 (P_{-3})^{3/2}\,, \tag{2}$$

where P_{-3} is the pressure in the disk (in 10^{-3} dy cm^{-2}). Eqs. 1 and 2 indicate that nuclear SBs may, at least marginally, satisfy the conditions for driving winds out of the galactic core of the Seyferts (if $n_{o,8} \lesssim 1$, $L_{K,43} \lesssim 1$, and $H_{pc} \lesssim 1$). But, how to explain the collimated morphologies of the observed outflows? One may invoke a thick gas torus surrounding the nucleus to collimate the "wind" in a similar way to that proposed in standard models for AGN (see, e.g., Colbert et al. 1996 and references therein). We will examine here, another possible mechanism in which collimation is provided by magnetic fields.

2. MAGNETICALLY DRIVEN OUTFLOWS

Collimated winds may be produced by a rotating disk with a magnetic field anchored into it (see, e.g., Spruit 1996 and references therein). Just outside the disk, the gas density is typically low enough, so that the magnetic energy density is large compared with the thermal and rotational energies. The gas of the disk will be, therefore, forced to co-rotate with the open field lines raising out of the disk surface. Assuming the disk is Keplerian, then at the foot point of the line, the inward gravity force will balance the centrifugal force. Above the disk, along the field line, the centrifugal force will increase with the distance from the axis and eventually exceed the gravity force thus accelerating the gas outward. This centrifugal acceleration stops when the flow speed becomes comparable to the Alfvén speed ($v = v_A = B^2/4\pi\rho$, where ρ is the gas density). Beyond the Alfvén point ($\rho v^2 > B^2/8\pi$), the inertia of the gas causes it to lag behind the rotation of the field line, and the field winds up thus developing an azimuthal component (B_ϕ), which will provide the collimation of the outflowing gas. Assuming also a cold disk (since the sound speed $c_s < v_A, \Omega r$, where Ω is the Keplerian rotation rate), we may quantify analytically the mass flux per **B**-line, $\rho v_p/B_p$, where v_p and B_b are the poloidal components of the flow velocity and the magnetic field, respectively

$$\mu \equiv (\frac{\rho v_p}{B_p}) / (\frac{B_o}{4\pi\Omega r_o}) = (\frac{\Omega r_o}{v_f})^3 , \tag{3}$$

where μ is the *dimensionless* mass flux per **B**-line defined in terms of a *natural* mass flux unit in the model ($B_o/4\pi\Omega r_o$; where the index "o" refers to the quantities at the line foot point). In this approximation, the Alfvén point location is at a radius $r_A/r_o = [3/2(1+\mu^{-2/3})]^{1/2}$.

The observed radio outflows of Colbert et al. (1996) have $v_f \simeq 25 - 150$ km s^{-1}, $B_f \simeq 3.5\times10^{-7} - 1.6\times10^{-6}$ G, and magnetic flux conservation gives $B_o \sim 0.35 - 12$ G at the base of the wind. From the equations above and our SB models, we find that the observed outflows are better fitted by the following conditions $\Omega r_o \simeq 10 - 46$ km s^{-1}, $\mu \simeq 10^{-3} - 10^{-1}$, and $r_A/r_o \simeq 12 - 3$, where we have assumed $r_o = R_d$. The fact that for a cold disk, the open field lines must have an inclination angle with respect to the disk $\theta \leq 60^{\circ}$, results that the height of the Alfvén point is $z_A \simeq 5 - 20$ pc.

The pitch angle of the field at the Alfvén point is $(B_\phi/B_p)_A = (2 - 3\omega^{1/3} - \mu^{-2}\omega^{-1} + \omega)^{1/2}\mu\,\omega^{1/2}$, where $\omega = (r_A/r_0)^3$. The range of values we have derived above for μ and ω results $(B_\phi/B_p)_A \simeq 1.8$. This value implies that the toroidal field lines should wind up from z_A to the large scale extensions of the observed outflows $z_{out} \simeq 5 - 30$ kpc about 10 times, thus providing enough collimation.

One of the attractions of the magnetically-driven outflow model is that it is able not only to produce and collimate the outflow, but also to take out angular momentum from the disk, allowing it to collapse. On the extreme condition that the outflow carries out all the angular momentum of the infalling gas in the disk, the ratio of the mass loss rate in the wind to the accreted mass rate in the disk is $\dot{M}_{out}/\dot{M}_{acc} = 1/2(r_A/r_o)^2 \simeq 3\times10^{-3} - 0.23$. Further, the condition above implies that the energy flux in the wind is equal to the rate of gravitational energy released by the infalling gas, $L_{out} = L_{acc}$. Observations give $L_r \simeq 10^{42-43}$ erg s^{-1} $\simeq L_{out}$, which is compatible with L_{acc} from our SB models for disk masses $M_d = 10^{8-9} M_\odot$.

3. CONCLUSIONS AND DISCUSSION

SBs with a disk core formed by infalling gas produced during star formation in a rotating cluster, seem to be, at least marginally, able to drive the weak, directed outflows of Seyferts galaxies. The collimation may be provided by magnetic fields (with intensities inferred from observations $\sim 0.35 - 12$ G) anchored into the rotating disk, which can also accelerate the flow up to the observed velocities and efficiently carry out angular momentum of the disk leading to a fast disk collapse.

We should further inquire about the fate of the SB disk. It rapidly becomes Jeans unstable and thus self-gravitating once $n_o > 10^6 (\Omega R_d/10 km\, s^{-1})^2 (R_d/1pc)^{-2}$ cm $^{-3}$. As a consequence, it may suffer fragmentation and star formation. Either, the disk may become bar unstable, a condition which is met if $\delta = T_{rot}/W > 0.14$, where T_{rot} is the rotational energy and W is the gravitational potential energy of the disk (e.g., Shlosman et al. 1989). Our SB disks result $\delta \simeq 0.25$, so that they can, in principle, become unstable to bar formation and undergo fission into two components which eventually may collapse to a supermassive BH. Based on the fact that the formation of BHs seems to be unavoidable in the SB model, we can speculate that both, the standard BH and the SB mechanisms may be occurring in different stages of the AGN evolution. In this evolutionary scenario, the stronger more collimated jets of radio loud QSOs, for example, could be produced in the higher-level activity phase of the BH. This hypothesis is examined elsewhere (Gouveia Dal Pino & Medina Tanco 1997).

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