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INDUCED STAR FORMATION IN CIRCUMNUCLEAR REGIONS OF SEYFERT GALAXIES

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RESUMEN

En este trabajo se estudia la inducción de formación de brotes estelares en anillos circunnucleares en galaxias Seyfert. Se dan argumentos en contra del "modelo unificado", según el cual *todas* las galaxias Seyfert 2, son, en realidad, de tipo 1 con una región que emite líneas permitidas anchas (BLR) oculta por un toroide de polvo orientado de tal modo con respecto al observador, que tapa esta región. Sin negar que existan casos de ocultamiento, se propone el siguiente esquema alternativo: la radiación debida a acreción hacia un agujero negro supermasivo decrece, mientras que la contribución relativa de un brote de formación estelar circunnuclear crece, entre los tipos 1 y 2 de núcleos Seyfert.

ABSTRACT

In this work we study the induction of enhanced star-formation around the nuclei of Seyfert galaxies. Arguments are given against the "unified model". According to this model, *all* Seyfert 2 galaxies are actually type 1, and harbor a broad line region (BLR) obscured by a dusty torus oriented in such a way, with respect to the observer, as to hide this BLR. Without denying that such cases occur, we propose an alternative scheme in which radiation due to accretion onto a supermassive black hole decreases, while the relative contribution of a circumnuclear starburst radiation increases, from Seyfert nuclei types 1 to 2.

Key words: **GALAXIES: SEYFERT — GALAXIES: STARBURST**

1. INTRODUCTION

Emission lines from galactic nuclei were discovered soon after the turn of the century (Fath 1909; Slipher 1917). However, little or no attention was paid to this discovery, even after Seyfert's paper (Seyfert 1943) in which he stressed the differences between the nuclear emission lines and those observed from ordinary gaseous nebulae. The reason was, very probably, the lack of interest in the nuclei of galaxies at that time; these findings were mere oddities. When the first systematic extragalactic photographic work was started, astronomers were mainly interested in the study of the outer and fainter parts of galaxies, thus often overexposing the nuclei.

After the discovery of double-lobed radio sources, Ambartzumian (1958) had the intuition to point out that the phenomenon was somehow related to the nuclei of the associated optical galaxies. A few years later, quasars were discovered. The optical spectra of quasars were found to be very similar to those of Seyfert galaxies, in particular Seyfert "type 1" galaxies (Khachikian & Weedman 1971). The optical spectra of radio galaxies also turned out to be similar! From then on, all attention was turned to the nuclei of these objects. First, the term "N galaxy" was introduced; today we refer to all these somehow-related objects —including also LINERs (Low Ionization Nuclear Emission Regions) and blazars, and some astronomers include also "nuclear starburst" galaxies— as active galactic nuclei (AGNs). The attention was focused almost obsessively on the nuclei of these objects due to the energetic problem posed by both the enormously high intrinsic brightness implied by their cosmological distances, and the extremely small sizes of the regions emitting this energy, that were inferred from variability studies. In 1964, almost simultaneously, but in an independent way, accretion onto a black hole was invoked to solve this problem (Zeldovich & Novikov 1964; Salpeter 1964). In its present form, this model involves jets, accretion disks, relativistic beaming and orientation effects (see e.g., Lynden-Bell 1978; Rees 1978; Begelman 1991; Collin-Souffrin 1991; Blandford & Rees 1992).

Since the sixties, attempts have been made by various authors to explain AGNs without invoking black holes. Some kind of starburst model has been considered by several authors (e.g., Shklovskii 1960; Field 1964) to explain radiogalaxies and quasars. Other stellar models including planetary nebulae, supernovae, and stellar clusters evolving in extreme conditions, (e.g., Pronik 1973; Harwit & Pacini 1975; Adams & Weedman 1975; Osterbrock 1978; Weedman 1983) were also considered, but eventually were abandoned because they failed to explain properly the main observed phenomena in quasars and other active nuclei. The main reason for these attempts is that no matter how nicely black hole models may work, some astronomers are annoyed by the fact that we don't really know if black holes exist at all. In its "modern" version, a model to explain the majority of AGNs without black holes has been developed by Terlevich and his colleagues (Terlevich et al. 1995, and references therein).

On the other hand, nuclear "hotspots" in the centers of galaxies were first identified by Morgan (1958) and later cataloged by Sersic & Pastoriza (1967). Finally the term "starburst nuclei" (SB) was introduced by Weedman et al. 1981. Further work (e.g., Kenicutt, Keel, & Blaha 1989) has revealed that "hotspots" are a mixture of very luminous star clusters and high-surface brightness, metal-rich, low excitation and ionization H II regions. These spectacular star forming regions are usually found in a ring or ring-shaped structure that lies from a few hundred to a few thousand parsecs from the nucleus, and are seen almost exclusively in barred galaxies. The most common interpretation is that hotspots are the consequence of the large gas inflows that are believed to occur in strongly barred galaxies. The rings always lie close to the expected locations of the inner Lindblad resonance (ILR) in the bar (e.g., Kenney et al. 1992; Roy & Belley 1993; Dressel & Gallagher 1994). Several theoretical studies have convincingly shown that gas can be channeled into a ring at the ILR in a barred galaxy (e.g., Combes & Gerin 1985) where it can be triggered into star formation (e.g., Elmegreen 1994). Examples also exist of hotspot rings in galaxies which are not clearly barred. One example is UGC 00861; Dressel & Gallagher (1994) suggest that this may be a case where the nearby passage of a companion triggers the formation of a temporary stellar bar, which in turn induces the formation of a star-producing ring of gas (Noguchi 1988). We want to stress that one condition does seem to be necessary for the occurrence of nuclear starbursts: a non-axisymmetric perturbation to the potential.

In an excellent review with the suggestive title "The Starburst-AGN Connection", Heckman (1991) carefully analyzes the evidence in favor and against the "pure" starburst models for "AGNs without black holes"; see also Cid Fernandez et al. (1992). We, as most astronomers today, don't believe that all the AGN phenomena can be explained with stars and/or debris of stars —no matter how extreme the conditions in which they evolve. With stars alone, one cannot explain the gamma ray emission (Thompson et al. 1994; Churazov et al. 1994), the jets, and all the highly relativistic effects associated with them (Marscher 1993), intraday radio and optical variability (Wagner & Witzel 1995, and references therein), as well as extreme X-ray variability (Rao, Singh, & Vajha 1992). Nevertheless, the work done by Terlevich and his collaborators has been very important for several reasons. It has directed attention to a phenomenon that is known to occur in many galaxies regardless of whether they are AGNs or not. Remarkably little work has been devoted to the evolution of such nuclear starbursts, other than the work of the above mentioned group, yet conditions in the nuclei of galaxies are, beyond any doubt, dramatically different from those in star forming regions in the solar neighborhood, even more so at distances > 100 pc. One example is the evolution of supernova remnants in very dense media (Terlevich et al 1992; Franco, Arthur, & Miller 1994). In our opinion, the most important consequence of the "black hole vs. starburst" debate is the presently emerging picture that these processes not only do not exclude each other, but are probably both important, albeit to different degrees for different types of objects.

In what follows, we shall try to support a scheme in which the difference between Seyfert type 1 and type 2 galaxies (Sy 1 and Sy 2) is that the intensity of the gravitational nuclear engine decreases from Sy 1 to Sy 2, while the relative contribution of circumnuclear starbursts increases; the starbursts may be non-existent in Sy 1 galaxies. This scheme is not in contradiction with orientation and obscuration effects for those cases in which spectropolarimetry reveals a hidden Sy 1 nucleus in a Sy 2 galaxy (e.g., Antonucci & Miller 1985).

2. THEORETICAL BASIS

The main theoretical problem posed by both accretion onto a supermassive black hole and the onset of violent star formation in the nucleus of a galaxy, is the supply of large amounts of gas to the nucleus. It is becoming clear, at least in principle, how large amounts of gas can be driven down to distances of a few kpc from the nucleus via some kind of non-axisymmetric perturbation to the potential: interactions (e.g., Sellwood 1989; Hernquist & Barnes 1994; Keel 1994), and bars and/or rings (e.g., Athanassoula 1992; Wada & Habe 1992; Christodoulou 1993). The problem is one of removing angular momentum. The specific angular momentum 3 kpc from the center is 10^{29} cm^2 s^{-1}, while at the last stable orbit around a 10^8 $M_\odot$ black hole it is 10^{24} cm^2 s^{-1}. Further orders of magnitude concentration required for activity are generally covered "by prayer and handwaving" (see excellent review by Phinney 1994), though some good attempts have been made to solve this problem (e.g., Begelman 1994; Shlosman and Heller 1994). In what follows, we shall approach this problem from the observational point of view.

3. OBSERVATIONS

Direct detection of close circumnuclear rings of star formation around AGNs has been difficult, basically due to problems of contrast and spatial resolution. However, the spectacular technological developments of the last 15 years have permitted advances in the detection of such rings around Seyfert and LINER nuclei (e.g., Wilson 1987). One of the first lists of such objects was given by Keel (1987). In his Table 1 he lists eight "Nuclei with H II rings"; of these, seven are LINERs or Seyfert 2 nuclei, and one is a SB nucleus. All of them have H II rings at distances of 0.15 to 1 kpc from the nucleus. All of the objects but one appeared in the "hotspots" galaxy list by Sersic & Pastoriza (1967). Several other such cases are presently known, some detected via optical and infrared images and/or long slit spectroscopy (e.g., González-Delgado & Pérez 1992; Rafanelli et al. 1993; Lipari, Tsvetanov, & Macchetto 1993; Marziani et al. 1994; Dressel & Gallagher 1994; MacKenty et al. 1994, etc.), others using high spatial resolution radio mapping (e.g., Wilson 1987; Levine, Turner, & Hurt 1993). Each case emerges from an individual investigation, thus not enough cases are known to make statistics. However, we do want to stress that almost all known cases have LINER and types 1.5 or 2 Seyfert nuclei. One exception is NGC7469 (e.g., Moles, Márquez, & Pérez 1995; Benítez et al. 1995), a very well studied Sy 1 galaxy, though occasionally misclassified as Sy 2 (Mouri & Taniguchi 1992) due to the strength of the circumnuclear starburst (see also Genzel et al. 1995).

A large accumulation of data, on the other hand, has permitted various types of statistical studies that support the hypothesis of induced activity (although it may not necessarily include the formation of SB circumnuclear rings). The main observations adduced to support induced activity are as follows: interacting galaxies have higher star formation rates (SFR) (Laurikainen & Moles 1988; Hummel et al. 1990; Keel & van Soest 1992); barred galaxies have higher SFR (Kennicutt et al. 1987; Fricke & Kollatschny 1989; Devereux 1994); Seyfert galaxies have more companions than field galaxies (Dahari 1985; MacKenty 1989); most classical double radio galaxies show evidence of interaction (Heckman et al. 1986; Baum, Heckman, & van Breugel 1992); quasars also seem to show evidence of interaction (Hutchings & Neff 1992); and most ultraluminous *IRAS* sources are mergers (Melnick & Mirabel 1990).

4. ENHANCED STAR FORMATION IN SEYFERT GALAXIES

The existence of enhanced star formation in Sy 1 galaxies has been difficult to prove; probably the case of NGC 7469 mentioned above, is the only one known. However, there are plenty of clear indications that this is the case for Sy 2 galaxies.

Most of the objects in the list given by Keel (1987), and the other objects mentioned above, where circumnuclear rings have been directly detected, are indeed Sy 2 or LINERs. Heckman et al. (1989) found that Sy 2 galaxies have larger L_{CO}/L_B ratios than Sy 1s; Su & Simkin (1980) and Arsenault (1989) find that bars and rings are more frequently seen in SB and Sy 2 than in Sy 1 galaxies. Along this line there is a very interesting result (although perhaps controversial) that it is Sy 2 —but not Sy 1— galaxies that have more companions (Petrosian 1982; MacKenty 1990; Laurikainen et al. 1995; Laurikainen & Salo 1995). Rodriguez-Espinosa, Rudy, & Jones (1987); Dultzin-Hacyan, Moles, & Masegosa (1988) and Dultzin-Hacyan, Masegosa, & Moles (1990) showed that, while the far-infrared (FIR) emission of Sy 1 galaxies is dominated by either synchrotron radiation or dust re-emission of this radiation; in the case of Sy 2 galaxies FIR emission is dominated by dust re-emission of starlight (particularly nuclear starlight in the case of 25 μm); recently, Dultzin-Hacyan & Benítez (1994) have shown that the near-infrared (NIR) emission of a sample of Sy 2 galaxies is dominated by the emission of a post-starburst population, probably circumnuclear (see also Mouri & Taniguchi 1992).

All this evidence points in the same direction: it is very important to investigate further in order to establish whether Sy 1 and Sy 2 galaxies have intrinsic differences in their star formation rates, morphology and/or environment.

There are other arguments against the idea that all Sy 2 are obscured Sy 1 galaxies (the so called "unified scheme"). First, there are counter-examples, i.e., cases where a BRL has been looked for and is *not* seen in polarized light (e.g., Miller & Goodrich 1990). Recently Norris & Roy (1994) found that Sy 2 galaxies have compact radio cores more often than Sy 1 galaxies and, to complicate the panorama, there are cases where the Seyfert type changes from type 1 to type 2 and vice versa in only a few months! (e.g., Sekiguchi & Menzies 1990; Iijima & Rafanelli 1992). In a recent statistical study, Dultzin-Hacyan & Ruano (1995) used principal component analysis (PCA) to investigate the multiwavelength properties of Seyfert galaxies. The main conclusion of that work is that the spectral energy distribution (SED) of Sy 1 galaxies is well accounted for by one and only one underlying variable, at least to a first approximation. On the other hand, in the case of Sy 2 galaxies, at least three variables are required. Several details of the analysis lead the authors to interpret this result in a sense that supports the above mentioned scheme: a sequence of decreasing accretion power and increasing relative circumnuclear starburst power for Seyfert galaxies going from types 1 to 2. In the framework of that interpretation, PCA revealed that the variance in the SED due to radiation of stellar and interstellar radiation (mainly dust absorption and re-emission), does not exceed $\sim 13\%$ for Sy 1 galaxies. In contrast, for Sy 2 galaxies stellar/interstellar radiation can account for as much as $\sim 46\%$ of the variance in the SED.

5. A CONDITION TO INDUCE ACTIVITY

5.1. Interactions

There are three basic types of interaction between galaxies: "far encounters", "close encounters", and "mergers". This is not the place to approach this topic in any detail, and we refer the reader to other papers: e.g., the seminal papers by Toomre & Toomre (1972); Heckman (1990); Hernquist & Barnes (1994). Here we only want to illustrate the effects of the various types of interactions on nuclear activity by means of an example of each of the types mentioned above. Often the visible effects of interaction are tidal tails and/or bridges, but the effects concerning both nuclear star-formation enhancement and activity have to be looked for in more detailed studies.

An example of a "far encounter" is the case of the pair of spirals Arp 298 (Benítez et al. 1995).

An example of a "close encounter" is given in Marziani et al. (1994). This is a case of a mixed morphology physical pair of galaxies (Kar 29), where there are clear indications that the elliptical made a nearly head-on passage through the disk of the spiral, producing at least two rings of enhanced star formation at ~ 4 and ~ 10 kpc. The spiral is a LINER. In a long slit spectrum taken along the axis joining a protuberance in the disk of the spiral with the elliptical (roughly along the minor axis of the spiral), various knots and diffuse extended emission are found. Emission lines along this axis exhibit structured profiles with a radial velocity range of 1200 km s^{-1}, all in the direction of the elliptical. Horellou & Combes (1993) carried out independent three-dimensional N-body simulations involving both stars and gas, to examine the effect of the perpendicular passage of a companion on the vertical gaseous and stellar extension of a target disk galaxy. Before both papers were published, the authors learned about each other's results and realized that the simulations reproduced very well the observations mentioned above. Although the simulation does not take star formation into account, gas is found to pile up and form rings at ~ 4 and ~ 10 kpc from the center —an amazing coincidence!

One of the most impressive examples of a "merger", and its relation to nuclear activity, is probably the so-called Superantennae (Mirabel, Lutz, & Maza 1991). The name comes from it's morphological resemblance to another merger prototype: NGC 4038/39, the Antennae. This remarkable example is the optical counter-part of an ultraluminous infrared (IRAS) galaxy. Mirabel et al. (1991) showed that the tails emanate from a merger of giant, gas-rich galaxies that harbor two nuclei: one Seyfert and one starburst, separated by 10 kpc. More than 80% of the energy radiated by this powerful infrared system comes from the deeply obscured Seyfert nucleus.

5.2. Other Non-Axisymmetric Perturbations

No matter how relevant interactions may be for nuclear activity, not all active galaxies are interacting. In a very interesting recent paper, Moles et al. (1995) examined the relation between dynamical perturbations, morphology, and nuclear activity in spiral galaxies. They investigated all the Seyfert and LINER galaxies with known morphology, and confirmed that the vast majority appear in early-type spirals (out of 279 galaxies, only 19% are later than Sb, and only 0.7% are later than Sc). The most impressive result of this study, however, is the finding that all the galaxies analyzed are either in interaction or have non-axisymmetric distortions — usually with bars and/or rings, or both. This result strongly suggests that the presence of non-axisymmetric perturbations of the potential, preferably in early-type spirals, is a necessary condition for the onset of nuclear activity. A very interesting open question naturally arises: is it also a sufficient condition?

Understanding the connection between dynamical perturbations, activity and morphological type is not straightforward. The observed scarcity of disrupted galaxies presenting nuclear activity (e.g., Keel et al. 1985; Bushouse 1987; Laurikainen & Salo 1995), however, could be understood through the connection between morphological type and activity. This could simply correspond, in principle, to the relative importance of the central mass, i.e., the bulge to disk ratio. On early-type galaxies, the effects of interactions are not disrupting; on the contrary, galaxies seem to respond coherently, being able to accommodate large scale perturbations by producing a global response, for example, in the form of a bar that drives gas into the center. On the other hand, a late-type spiral, which lacks a massive bulge, could not produce a global coherent response, and thus could not prevent the onset of local fragmentation, producing star formation all along the galaxy. This is beautifully illustrated by the case of the (early+late) spiral pair Arp298 (see Benítez et al. 1995 and Moles et al. 1995). Illustrating is not proving, however, and thus this is another open question. We do want to mention here another interesting, related result, obtained by Elmegreen, Elmegreen, & Bellen (1990), that mass transfer and star formation during a near encounter can change an unbarred late type into a barred early type galaxy.

We conclude without conclusions. Instead, we conclude with more open and challenging questions: first, is it true that *all* Sy2 are obscured Sy1 nuclei? If, as supported here, many Sy1 and Sy2 galaxies do indeed have differences that cannot be accounted for by obscuration and orientation effects alone, then do these differences relate to the way in which activity is induced? Or do they depend —only or also— on some initial conditions of the host galaxy? If so, on which conditions? And finally, the most intriguing question: Is there any evolutionary link between nuclear black holes and circumnuclear starbursts in active galaxies? And if so, in what sense? And in what circumstances can both be present? Discussions of these topics can be found, e.g., in Heckman (1991, and references therein); Perry (1992); Osterbrock (1993); and Whittle (1994).

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