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STAR FORMATION IN GALACTIC NUCLEI

(Invited Talk)

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RESUMEN. El escenario del "starburst-warmer" para los núcleos activos de galaxias (AGN) postula que la actividad nuclear observada, es la consecuencia directa de la evolución de un brote violento de formación estelaar en el medio interestelar de alta metalicidad y densidad en las regiones nucleares de las galaxias. La región de línea ancha (BLR) observada en galaxias Seyfert tipo I y objectos cuasi-estelares (QSO) se origina en una población de remanentes jóvenes de supernova (SNR) que evolucionan en el gas de alta densidad en las condiciones del núcleo. Durante la étapa de supernova (SN), cuando el flujo ionizante es dominado por la actividad de las supernovas, se espera gran variabilidad en objetos con una tasa de SN de 1 año^{-1}. He revisado los resultados observaciones recientes que nos dan clara evidencia de este escenario. En particular, los remanentes de supernova 1987F y 1988I tienen propiedad ópticas muy semejantes a aquellos del núcleo de Seyfert I.

ABSTRACT. The starburst-warmers scenario for Active Galactic Nuclei (AGN) postulates that the observed nuclear activity is the direct consequence of the evolution of a starburst in the high metallicity and high density interstellar medium in the nuclear regions of galaxies. The broad line region (BLR) observed in Seyfert type 1 and Quasi-stellar objects (QSO) is originated in a population of young supernova remnants (SNR) evolving in the high density gas of the nuclear environment. During the supernova (SN) stage, when the ionizing flux is dominated by SN activity much variability is expected in objects with SN rates of $\sim$ 1 yr^{-1}. I review recent observational results that provide supporting evidence to this scenario. In particular, the peculiar SNe 1987F and 1988I have optical properties that closely resemble those of Seyfert 1 nuclei.

Key words: **GALAXIES-ACTIVE – GALAXIES-NUCLEI – STARS-FORMATION – STARS-SUPERNOVAE**

INTRODUCTION

It has become customary to divide galactic nuclei into two main groups: "normal" and "active", referring nuclei whose properties can and cannot be explained in the context of normal star formation and evolution spectively. However, a clear division between these two classes does not exist, and a continuity and/or overlap of ·operties between both has been reported in radio (Condon *et al.* 1982), infrared (Rieke and Lebofsky 1979) and X-y (Lawrence *et al.* 1985) surveys of luminous galaxies. In fact, the possibility of a connection between the presence of ›t young stars and nuclear activity has been recognized by several authors (Shklovskii 1960, Field 1964, Pronik 1973; lams and Weedman 1975; Harwit and Pacini 1975; McCrea 1976; Osterbrock 1978; Weedman 1983).

The term AGN covers these days a large variety of objects: Seyfert galaxies, QSO, Quasars, Blazars, ıdio Galaxies, X-Ray Galaxies, LINERs, etc. The list of observed properties of AGN is equally varied: bolometric minosity, level of radio power, level of X-ray power, relative importance of IR emission, presence or absence of broad nission lines, degree of variability, polarization, etc. In spite of all the variety, it is however clear that the large majority 'AGN are radio quiet and are neither violently variable nor highly polarized. I will refer to these AGN as ORDINARY GN. They may represent up to 95 % of all AGN and they are found mainly in optical surveys of QSO or studies of ıclei of galaxies, they are usually classified as Seyfert galaxies or QSO depending on the nuclear luminosity and also ı whether or not the parent galaxy is detected.

Perhaps the most important property of AGN is that they emit an enormous amount of energy from ›parently small volumes and over an extremely wide frequency range. The emitting volumes have been constrained by the observed time scale of variability that place upper limits on the size of the emitting region on the assumptio that it is a single object. Any serious attempt to explain AGN must simultaneously account for their high luminosit large variability and wide spectrum, extending from radio up to at least hard X-rays.

For the past decade there has been agreement among most researchers that the energy source in AG is primarily gravitational and might involve extremely dense stellar clusters, supermassive stars or Black Holes. Bı the consideration that the inevitable end product of the evolution of both a dense stellar cluster and a supermassiv star is also a massive Black Hole, has shifted the aim of the theoretical and observational work towards the study of th properties of the putative massive Black Hole and its environment.

An alternative scenario has been developed in some detail by Terlevich and collaborators. We postula that large nuclear starbursts followed by proportionally large numbers of Supernova explosions and Supernov remnants can account for the observed properties of ordinary AGN, and that there is no need to invoke exotic objec such as those mentioned above. The scenario was described by Terlevich and Melnick (1985) and Terlevich, Melnic and Moles (1987); extended to Seyfert 1 in Terlevich and Melnick (1987,1988) and to QSO luminosities in Terlevic (1989*a,b*). In this paper, I will summarize the evolution of a nuclear burst of star formation and estimate its supernov rate, luminosity and size.

II. THE EVOLUTION OF STARBURSTS

Terlevich and Melnick (1985; hereafter TM85) investigated the properties of giant bursts of st formation with metallicities typical of those found in the nucleus of giant galaxies. Young metal rich massive stars hav their evolution fundamentally affected by mass-loss in the form of stellar winds. Without exception all evolutiona computations find the same differences initially found by Tanaka (1966) between conservative, $\dot{M}=0$, and mas losing models: after hydrogen exhaustion, the star becomes hotter, reaching effective temperatures well in exce of those typical of the ZAMS. Wolf-Rayet stars with massive progenitors ($M>60\,M_\odot$) are believed to be in the bluewar evolutionary stage (Conti 1976, Maeder 1983). Evolutionary star models for solar composition and incorporating ma loss and overshooting, indicate that during the helium burning phase the effective temperature reaches up to 200 000 and the bolometric luminosity could be up to a factor of 2 larger than at the ZAMS. Terlevich and Melnick called the extremely hot and luminous Wolf-Rayet stars WARMERS.

Using theoretical isochrones, TM85 computed the changes that a population of warmers will introdu into the emitted spectrum of a young metal rich cluster. It was found that the emitted spectrum of a metal rich H region suffers a qualitative change after about 3Myr of evolution, when the most massive stars reach the warmer phas In a very short time the ionizing spectrum of the cluster is fundamentally modified by the appearance of the warm component. Consequently the emission line spectrum is transformed from that of a typical low excitation H II regio into a high excitation Seyfert type 2. Following the evolution still further, shows that after 5Myr, as the ionizing flu decreases and therefore the ionization parameter also decreases, the Seyfert type 2 nucleus becomes a Liner. In brie TM85 have shown that the 'traditional' method of using the Baldwin, Phillips and Terlevich (1981) diagnostic diagran to classify nuclear emission line regions should be used with care. Power law type ionizing continuum can be the resu of a few warmers modifying the emitted *UV* spectrum of a young cluster.

Terlevich, Melnick and Moles (1987), extended the work of TM85 to include the supernova phase in th evolution of the nuclear starburst. According to the initial mass of the progenitor, two different supernova phases a expected

1 - a SN type Ib phase at the end of the life-time of the most massive stars ($M>25\,M_\odot$). These SNe have Wolf-Ray warmer progenitors and they are predicted to be optically dim and radio loud. The remnant will be similar to Cas or the SR in the galaxy NGC 4449 showing weak broad optical emission from [O III], [S II] and [Ne III] but no broa hydrogen lines. During this phase the spectrum of the starburst will look like that of a typical Seyfert type 2 , wi substantial radio emission.

2 - a SN type II phase at the end of the life-time of intermediate mass stars ($5 < M < 25\,M_\odot$). These SNe have re supergiant progenitors. The SN ejecta after leaving the atmosphere of the star will presumably interact with den circumstellar interstellar medium. This interaction will produce a hot and luminous remnant with a life time of abo 2 years and broad permitted emission lines. During this phase the spectrum of the starburst will look like that of Seyfert type 1 or QSO.

Theoretical computations of supernova remnants propagating into a pre-supernova environment of hig density predict a fast shock propagating outwards into the unshocked material and a reverse shock moving backwar into the SN ejecta. The supernova remnant sweeps-up only a small amount of mass before becoming radiative an depositing most of its kinetic energy in a very short time scale thus reaching very high luminosities. Most of th luminosity will be emitted in the extreme *UV*/X-ray region of the spectrum.

Following Shull (1980) and Wheeler *et al.* (1980), the onset of the radiative phase of a SR evolving in constant circumstellar density, is at

$$t_{on} = 230\ days\ \epsilon_{51}^{1/8}\ n_7^{-3/4}$$

when the shock has velocity, size, temperature, and luminosity given by:

$$V_{sh} = 4600\,\epsilon_{51}^{1/8}\,n_7^{1/4}\left(\frac{t}{t_{on}}\right)^{-5/7}\ \mathrm{km\,s^{-1}}$$
$$R_{sh} = 0.01\,\epsilon_{51}^{1/4}\,n_7^{-1/2}\left(\frac{t}{t_{on}}\right)^{2/7}\ pc$$
$$T_{sh} = 3.0\times10^{8}\,\epsilon_{51}^{1/4}\,n_7^{1/2}\left(\frac{t}{t_{on}}\right)^{-10/7}\ K$$
$$L_{sh} = 2\times10^{43}\,\epsilon_{51}^{7/8}\,n_7^{3/4}\left(\frac{t}{t_{on}}\right)^{-11/7}\ \mathrm{erg\,s^{-1}}$$

where n_7 is the circumstellar density in units of 10^7 cm^{-3} and ϵ_{51} is the supernova energy in units of 10^{51} erg s^{-1}. The velocities, dimensions and luminosity of this remnant are very similar to those of the canonical BLR in low luminosity AGN. Combining these set of equations and assuming pressure conservation across the shock it is possible to show that the post shock shell will have density, ionization parameter, mass and column density given by:

$$n_{she} = 1.2\times10^{12}\,\epsilon_{51}^{1/4}\,n_7^{3/2}\left(\frac{t}{t_{on}}\right)^{-10/7}\ \mathrm{cm^{-3}}$$
$$U_{she} = 2.0\times10^{-3}\,\epsilon_{51}^{1/8}\,n_7^{-1/4}\left(\frac{t}{t_{on}}\right)^{-5/7}$$
$$M_{she} = 1.1\,\epsilon_{51}^{3/4}\,n_7^{-1/2}\left(\frac{t}{t_{on}}\right)^{6/7}\ \mathrm{M_{\odot}}$$
$$\Sigma_{she} = 1.1\times10^{23}\,\epsilon_{51}^{1/4}\,n_7^{1/2}\left(\frac{t}{t_{on}}\right)^{2/7}\ \mathrm{cm^{-2}}$$

Again the predicted parameters are very similar to those of the canonical BLR. Moreover, the photoionization of the cool post shock material by the radiation of this type of fast shocks has been shown to provide line ratios very similar to those observed in the BLR of AGN (Daltabuit, MacAlpine and Cox 1978). Also, given the high densities in the shell, no forbidden lines are expected. Thus in most aspects this rapidly evolving remnant closely resemble the observed BLR in ordinary AGN.

Terlevich and Melnick (1988) have provided evidence that this may be the case. They showed that the reported flare in the Seyfert type 1 NGC 5548, may have been the first detection of a type II SN in the nucleus of a galaxy, rather than an accretion event (Peterson and Ferland 1986). The spectrum of the flare looked very similar to that of SN 1983K the only supernova known with a probable Wolf-Rayet progenitor. Also the luminosity and duration of the flare were similar to those of SN 1983K.

Perhaps the most compelling evidence comes from some recent observations of supernovae. Filippenko (1989) has reported the discovery of a supernova in an H II region in one of the spiral arms of the SBc galaxy NGC 4615. After maximum the spectrum was dominated by broad permitted emission lines of hydrogen, Fe II and Ca II; it has a striking resemblance to the spectrum of a Seyfert type 1 or a QSO. A second supernova reported in the same paper, SN 1988I, showed a similar spectrum and the luminosity and light curve of the two SNe were similar to those of Seyfert 1 nuclei.

All these points strongly suggest that at least some low luminosity ordinary AGN can be the direct result of star formation in the nuclei of galaxies. To extend the model in order to include the high luminosity AGN, it is necessary to discuss two fundamental observational constraints:

1- the amplitude of the optical variability in QSO, and

2- the required star formation rate to explain the luminosity of QSO.

III. SUPERNOVA RATES IN YOUNG GALAXIES.

The supernova rate (SNR) can be estimated as

$$SNR = -\frac{dN}{dt} = -\frac{dN}{dM}\frac{dM}{dt} \qquad (1)$$

The first factor of this expression can be calculated assuming a power law initial mass function (IMF) of the form

$$dN = A\, M^{-\alpha}\, dM \tag{2}$$

with normalization factor

$$A = \frac{(2-\alpha)\, M_t}{M_u^{2-\alpha} - M_l^{2-\alpha}} \tag{3}$$

where M_u and M_l are respectively the upper and lower limit of the IMF, M_t is the total cluster mass and α is t logarithmic slope.

Analytical fits to the evolutionary star models of Maeder and Meynet (1988) for solar abundance, provi expressions for the initial mass of a star at the end of the helium burning phase M_{He}, as a function of time,

$$M_{He} = 18\, t_7^{-0.54}\, M_\odot, \tag{6}$$

the cluster turn-off mass, M_H, as a function of time.

$$M_H = 15\, t_7^{-0.54}\, M_\odot, \tag{7}$$

the time variation of the stellar mass at the pre-supernova stage,

$$\frac{dM}{dt} = -9.6 \times 10^{-7}\, t_7^{-1.54} \tag{7}$$

and the luminosity-mass relation during hydrogen burning,

$$\frac{L_*}{L_\odot} = 0.85\left(\frac{M}{M_\odot}\right)^{4.0} \tag{8}$$

These expressions are valid for ages $10 < t_7 < 100$, where t_7 is the age in units of 10^7yrs corresponding to the type Supernova phase or QSO Seyfert 1 phase.

After some algebra it is possible to show that the bolometric luminosity emitted by the superno remnants per unit mass of the cluster and the ratio of stellar to SR luminosity is for typical values, α=2.35 (Salpe slope), $M_u = 50\,M_\odot$, $M_l = 1\,M_\odot$ and $\epsilon_{51} = 3$:

$$\frac{SNR}{M_t} = 5.2 \times 10^{-10}\, t_7^{-0.27}\, M_\odot^{\ -1}$$

$$\frac{L_*}{L_{SR}} = 14\, t_7^{-1.47}$$

Typical parameter values are listed below.

t_7	$\frac{SNR}{M_t}$	$\frac{L_*}{L_{SR}}$
2.0	4.5×10^{-10}	5.0
4.0	3.6×10^{-10}	1.9
6.0	3.2×10^{-10}	1.0
8.0	3.0×10^{-10}	0.7

The most important aspect of this computation is that it shows that after about 40 Myr of evolution the middle of the Seyfert 1 phase, the luminosity output of the SN and SR is about equal to that of the young stars a that this result is almost independent of the choice of IMF parameters.

A typical L* elliptical galaxy has a mass of about 10^{12} $M_\odot$ and an effective radius (half mass radi of 5 kpc and its present absolute blue luminosity is M_b=−21.5. Following Larson (1974) dissipative models for formation of elliptical galaxies, during the formation of the inner kiloparsec at the end of the collapse, the SFR fo 10^{12} $M_\odot$ elliptical reaches a peak of about 3000 $M_\odot$year corresponding to a total mass in young star of 3×10^{11} I after the 10^8 yr life-time of the burst. For the IMF values assumed above this implies a SNR of 100 SN year during t SN type II phase. It is simple to estimate that the integrated blue luminosity of such a young elliptical galaxy duri the SN phase is about M_b=−25, the luminosity of a typical QSO.

IV. OPTICAL VARIABILITY IN QSO

Work on optically selected QSO, has indicated that most of them show only small amplitude (~0.2 m ariability (Bonoli *et al.* 1979). Perhaps the largest dataset is that obtained at the Rosemary Hill Observatory (Pica and mith 1983,PS83). It includes 13 years of continuous monitoring of 130 AGN with an average of 45 epochs per source. erlevich (1989*b*) estimated the variability of a Starburst during the supernova stage using Montecarlo techniques. The omparison with PS83 data set shows that the amplitude of the variability observed in QSO and in many quasars is vell inside that expected in the starburst scenario. Thus, the observed variability time scale is *not* constraining the ize of the BLR in ordinary AGN because it is not necessarily originated in a single compact object, it could also be he superposition of random SN events spread over few kpc, which produces the required variability amplitude and bserved time scales.

If monitoring is performed with accuracy of 0.01 magnitudes then I predict a peak-to-peak variability mplitude of

0.10 magnitudes for a	$M_b = -27.5$ *QSO*
0.30 magnitudes for a	$M_b = -25.0$ *QSO*
0.85 magnitudes for a	$M_b = -22.5$ *QSO*

vith time scale of few months.

/. THE SIZE OF THE BLR

The size of the BLR will depend on the SN rate as a function of radius in a young elliptical galaxy. In arson's model, the SN rate is at the maximum value at the end of the collapse and inside the effective radius. Assuming hat the SN distribution follows the mass distribution of the galaxy, we can then estimate its half intensity diameter that orresponds to twice the core radius (2 R_c). From the comparison of the $r^{1/4}$ law and the Hubble law of brightness listribution Kerr (1957) found that $R_h = R_e/11$ and as the R_c in Hubble's law is 0.4142 R_h then in a typical elliptical xR$_c$ $\sim R_e/13$. In our typical L* elliptical this corresponds to less than 400pc or 0.014 arcsec at a redshift of 1.

A different estimate can be done using the scaling laws of bursts of star formation. Terlevich and Melnick 1981) and Melnick *et al.* (1987) studied the scaling laws for giant H II regions and HII galaxies. They found relations f the form $L \propto R^2$ are valid over more than an order of magnitude in radius. Applying the scaling to the determination f the core radius of 30-Doradus by Moffat *et al.* (1985) (0.26pc), and using a $M_b = -14.5$, the predicted R_c for the $M_b = -25$ burst of the L* elliptical is less than 100pc.

Putting both estimates together the size of the BLR in the starburst scenario should be,

$$0.10\ arcsec\,10^{-0.2(m_b-14.5)} \leq FWHM \leq 0.40\ arcsec\,10^{-0.2(m_b-14.5)}$$

vhere m_b is the apparent blue magnitude. The expression is valid for objects more luminous than $M_b = -21$. The imit is to ensure that the BLR is not dominated by a single SN remnant.

/I. CONCLUDING REMARKS

The main aim of this review was to illustrate that the starburst scenario gives a good description of the nost important properties of ordinary AGN: their luminosity, variability and spectral properties. The starburst scenario rovides a new angle of attack into the fundamental problem of the energy source of AGN. Although it is probably true hat objects with strong collimated radio emission and polarized optical emission like BL Lacs and Blazars are not ssociated with star formation, there is no strong reason to believe that ordinary AGN do have an active nucleus. They ould be galaxies in the process of forming the central region of their spheroidal component.

The fact that the luminosities and variability of QSO can be explained with the expected SN rates during he formation of a spheroidal galaxy leads naturally to the suggestion that perhaps most of the optically selected QSO, epresenting the majority of the high redshift luminous objects, are young galaxies in the process of formation.

One important difference between the starburst and the blackhole scenario is the size of the BLR. The act that the BLR should be tens of parsecs FWHM in luminous Seyferts, constitutes a potential test for the scenario. Based in simple scaling laws I predict that the HST may be able to resolve the BLR of some of the nearest luminous eyfert galaxies.

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