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ACTIVE GALACTIC NUCLEI AND NUCLEAR STARBURSTS

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RESUMEN

De acuerdo al modelo de brotes de formación estelar, la actividad que se observa en núcleos galácticos activos podría estar generada por estrellas jóvenes y restos compactos de supernovas en un brote violento de formación estelar En este modelo, las líneas anchas de emisión y su variabilidad están ambas originadas en los restos compactos de supernova.

Los cálculos del enfriamiento radiativo detrás de los choques de supernova cuando son combinados con modelos estáticos de fotoionización, muestran que los remanentes compactos reproducen la mayoría de las propiedades básicas de la zona de líneas anchas en núcleos galácticos activos de poca luminosidad.

Proponemos que los QSO son los núcleos de alta metalicidad de las galaxias elípticas gigantes formándose a z > 2.0.

ABSTRACT

The Starburst model for radio-quiet Active Galactic Nuclei (AGN) postulates that the activity seen in most AGN is powered solely by young stars and compact supernova remnants (cSNR) in a burst of star formation at the time when the metal rich core of the spheroid of a normal early type galaxy was formed. In this model, the broad permitted lines characteristic of the Broad Line Region (BLR) and their variability originate in these cSNR.

Detailed calculations of strong radiative cooling behind supernova shock waves evolving in a high density medium, combined with static photoionization computations, have shown that cSNR can reproduce most of the basic properties of the BLR in low luminosity AGN. We make definite predictions about the *lag*, the observed delay between sudden changes in the continuum ionizing radiation followed, after some time, by changes in the intensity of the emission lines from the broad line region of AGNs.

We have proposed that QSOs are the young metal rich cores of massive elliptical galaxies forming at z > 2.0. Only a small fraction ($\sim$ 5%) of the total mass of a normal elliptical, the core mass, is needed to participate in a burst to explain the observed luminosities and luminosity function of QSOs at z $\sim$ 2.0. We predict that the progenitors of QSOs should look like dusty starbursts and be bout 4 times more luminous (in bolometric units) and 10 times less frequent than QSOs themselves.

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

1. INTRODUCTION

In the past few years we have started a systematic study of properties of high metallicity starbursts including the latest developments of the knowledge of massive star evolution and formation. A model was developed where the observed nuclear activity of QSOs and Seyfert galaxies is the *direct* consequence of the evolution of a massive young cluster of coeval stars in the high metal abundance environment of the nuclear region of early type galaxies (see Terlevich *et al.* 1992 hereafter TTFM, and Terlevich & Boyle 1993).

In the starburst model of AGNs, sometimes viewed as exotic and/or unconventional, the applied physics are in fact most conventional, as it uses the little, or the lot, that we know about real events: the physics of stars and stellar evolution and their interaction with the surrounding gas, and with these predictions are made.

Terlevich & Melnick (1985) computed the changes that a population of hot Wolf-Rayet stars (WARMERS) introduces in the UV spectrum of a young stellar cluster, and found that at about 3 Myr of evolution, when the most massive stars ignite the Helium in their cores, the ionizing spectrum of the cluster is fundamentally modified by the appearance of a luminous and hot component, the *Warmer* component. Consequently the emission line spectrum is transformed from that of a typical low excitation HII region into a high excitation Seyfert 2. After 5 Myr, as the ionizing flux decreases, the ionization parameter also decreases, and the Seyfert 2 nucleus becomes a LINER (Cid-Fernandes *et al.* 1992). These results suggested the possibility of a direct relation between star formation and stellar evolution with some forms of nuclear activity. Following the evolution still further, when the cluster enters the supernova phase the Starburst can display properties similar to those observed in the BLR of AGN (TTFM).

We proposed that the observed broad emission lines and their variability, are generated by "compact", strongly radiative supernova remnants which are expected to occur in the metal rich central regions of early type galaxies undergoing a violent nuclear burst of star formation. The activity of all stars and the frequency of supernova explosions soon establishes a high pressure region around the cluster. This high pressure, as it acts upon the slow winds from the massive stars ($M \geq 8\,M_{\odot}$), leads to the development of a high density circumstellar medium ($n_0 \geq 10^7$ cm^{-3}) around each of the potential supernova stars. It is in this high density circumstellar medium that the energy of each supernova is released, causing the most obvious property of "compact" supernova remnants: a burst of radiative energy which makes them reach luminosities well in excess of $10^9\,L_{\odot}$. This happens during a few years ($\leq$ 10 years) through which more than 90% of the initial energy of the explosion (10^{51} erg) is radiated away, while the remnants acquire dimensions of only a few times 10^{16}cm. The high circumstellar densities thus provoke the rapid onset of strong radiative cooling and, with it, the various hydrodynamical events that lead to the broad line region, the continuum, the line variability, and also to the *lag* typical of these sources. During this supernova or QSO phase, most of the luminosity is emitted by the young stars, while the broad permitted emission lines and their variability, i.e., the BLR luminosity, is due to cSNR activity and can be up to 50 percent of the total luminosity. Terlevich & Boyle (1993) have explored the hypothesis that QSOs are the young cores of massive ellipticals forming most of the dominant metal rich population in a short Starburst. They showed that the Starburst model can account for the numbers of high luminosity QSOs observed.

Here we present an overview of the model and describe some of the recent developments.

2. THE EVOLUTION OF LUMINOUS METAL RICH STAR CLUSTERS

The early evolution of a massive metal rich star cluster presents four different phases with well defined transitions (Terlevich, Melnick, & Moles 1987). The first phase is dominated by HII regions ending with the appearance of the first extreme Wolf-Rayet or *warmers* which marks the beginning of the type 2 Seyfert phase. The explosion of the first SN of type Ib corresponds to the onset of non-thermal radio emission while the first explosions of type II SN lead to the formation of the BLR and the start of the QSO phase.

Recent observations show that the spectrum of at least some luminous SN exploding in HII regions have a striking resemblance to that of the BLR of Seyfert galaxies (Filippenko 1989) and, conversely, that the flares of some Seyfert galaxies have the luminosity, lifetime, and spectral signatures of type II SN (Terlevich & Melnick 1988). The fundamental difference between "Seyfert-like" and normal type II SN can be understood if the former are associated with shocks that, after leaving the envelope of the star, expand into a region of *high circumstellar gas densities.* All theoretical computations of the evolution of SNR in dense environments show that after sweeping up a small amount of gas these remnants become radiative and deposit most of their energy in very short time scales thus reaching very high luminosities. Because of the large shock velocities, most of the energy is radiated in the extreme UV and X-ray region of the spectrum (Shull 1980; Wheeler *et al.* 1980; TTFM).

3. THE LIGHT CURVE AND VARIABILITY OF cSNR

The initial interaction of the SN ejecta with the ambient medium generates a hot shocked region enclosed by two shock waves: a leading shock moving outwards, and an inward "reverse" shock. The leading shock ($V \sim 10^4$ km s^{-1}) raises the gas temperature to $\sim 10^9$ K. The slower reverse shock ($V \sim 10^3$ km s^{-1}), thermalizes the supernova ejecta to temperatures of about $\sim 10^7$ K. The onset of the radiative phase in a dense medium occurs very early in the evolution and all evolutionary phases are substantially speeded up (TTFM). Given the strength of the radiation produced upon cooling, this phase plays a key role in the model. Such a strong cooling implies, as in the colliding cloud model (Daltabuit, MacAlpine, & Cox 1978), that a large flux of ionizing photons will emerge from the shocked gas. The wide range of gas temperatures in the cooling region results in a power-law-like spectrum at UV and X-ray frequencies (TTFM).

One of the most interesting properties of cSNR is their rapid burst of radiative energy, which makes them reach luminosities well in excess of 10^9 L$_\odot$. This happens in a few years ($\leq$ 10 yr) through which more than 90% of the initial energy of the explosion (10^{51} erg) is radiated away as the remnants acquire dimensions of the order of a few times 10^{16} cm. As most of the energy is radiated away before the kinetic energy of the ejecta is fully thermalized, cSNR do not enter the so called "Sedov" or quasi-adiabatic evolutionary phase. In a luminosity (L) *vs* time (t) diagram, remnants at first increase their luminosity as $t^{0.8}$ to reach within a few years ($\leq$ 3 yr) an $L \sim 10^9$ L$_\odot$. This is followed by a slower decay ($t^{-11/7}$) leading to factors of 4 to 10 lower luminosities for the various runs. Our hydro models present four major energy bursts superimposed on the secular decay of the remnant luminosity. These events are all very short, typically of only a few months duration, and involving about 1-10% of the initial explosion energy. These four bursts of luminosity are produced by: 1) The onset of strong radiative cooling, within the swept up circumstellar matter. This leads to the absolute maximum luminosity (several times 10^9 L$_\odot$ for $n_0 = 10^7$ cm^{-3}) of the remnant. 2) The completion of thin shell formation at the edge of the rapidly expanding ($\geq$ 2000 km s^{-1}) remnant. 3) The onset of strong radiative cooling behind the reverse shock, also leading to the condensation of the shocked ejected matter into a secondary inner shell, and 4) the merging, or collision, of both shells which leads to fragmentation and dispersal of the remnant. All these events occur prior to full thermalization, and, in all cases, more than 90% of the initial energy of the explosion is radiated away by the time the last burst is over.

We have compared the behaviour described above with the detailed spectroscopic observations of NGC 1566 which span over several years. The nucleus showed four major periods of activity, lasting about 1300 days, and releasing about 10^{51} erg each (Alloin et al. 1986). These we attribute to supernova explosions and their associated cSNR. The last of which was observed with high temporal resolution and showed 3, maybe 4, short energy bursts. Each burst presented a steep rise time ($\sim$ 20-30 days) and a longer decay of about 300-400 days. This behaviour is indeed very similar to that present in our numerical solution. Furthermore, a least square fit to the slope of the secular decay of NGC 1566 (i.e., after removing the 3 or 4 bursts of energy from the light curve) gives -1.57, while the numerics gives -11/7 = -1.57. The observed luminosities are also in very good agreement with our predictions.

The general expected behaviour of the optical variability is supported by most studies which show that high luminosity QSOs are less variable than low luminosity ones, in particular Seyfert galaxies. The analysis of the best data sets of photometry of QSOs with a long time base line is consistent with, if not suggestive of, the variability being originated in supernova size events (Terlevich 1990a,b; Aretxaga & Terlevich 1993).

4. THE NATURE OF THE *lag*

Detailed calculations of compact SNRs have shown in great detail the sequence of events that take place as remnants approach and reach maximum luminosity. The matter involved in the process, suddenly has to readjust to the large pressure inbalance promoted within the shocked gas by the onset of strong radiative cooling. The final outcome is the formation of a thin shell at the edge of the remnant, several orders of magnitude denser than the original background medium. Gas condensation however, does not happen immediately, as it requires of the passage of secondary shocks through the cool region for this to acquire the appropriate (density and thus) pressure. The secondary shocks emmanate from the hottest section of the remnant interior, overtaken earlier during the evolution when the shock speed was larger, and that takes much longer to cool. They follow the blast wave in an attempt to communicate the interior pressure, however, given the increasingly larger densities behind them and thus the correspondingly shorter cooling distances, become also rapidly radiative. Meanwhile cooling proceeds as a front, ahead of the secondary shocks, into gas more recently overtaken by the progressively slower blast wave to eventually catch up with it. The blast wave slows down for two reasons: because of geometrical dilution as the remnant grows and because it has now suddenly lost its piston pressure due to strong cooling behind it. The gas steadily overtaken by the cooling front is a source of ionizing continuum radiation, to be observed as a variation in the continuum of the AGN. This radiation is immediately absorbed by the reshocked matter, by the cool layer of gas continuously changing density after the passage of secondary shocks. The combination of a steadily denser layer constantly irradiated, as the cooling wave progresses through the layer of shocked gas, leads to a continuous decrease in the effective ionization parameter and results into a rapidly changing ionization structure of the photoionized gas.

The numerical calculations have shown that the width of the photoionized shocked region, traversed by the cooling front and continuously swept by secondary shocks to condense it into a cool thin shell, is only about 10^{13} cm (or about 10^3 secs $\times$ c), and yet, *lags* of up to several days, weeks, and even months, are generated for different lines. In general, the calculations predict shorter delays for high ionization lines than for low ionization ones. A detailed comparison with the results from the NGC 5548 extensive monitoring campaign agrees both on the time delays for different lines, and on the intensity values reached by the various lines. Our calculations thus show that the compact supernova remnant model is capable of giving an accurate and detailed description of the temporal behaviour of the broad line region as well as accounting for all of its intrinsic parameters with a minimum of free parameters.

5. THE QSO LUMINOSITY FUNCTION

One important objection raised against the Starburst model for AGN is that it cannot account for the numbers of high luminosity QSOs observed. The Starburst model requires star formation at high metallicity, and the obvious places with high metallicity are the cores of luminous ellipticals. Thus, a strong test of the objection would be to compare the predicted luminosity function (LF) for cores of elliptical galaxies at the time in which the "Starburst" activity is taking place with the QSO LF at high redshifts ($2 < z < 3$) where it is now generally accepted that QSO activity was at its peak (Schmidt, Schneider, & Gunn 1991). The QSO LF in the blue (rest) pass band at these redshifts has recently been determined by Boyle (1992) using the large number of faint QSO catalogues which have been compiled in the last few years. In order to obtain the predicted LF for the cores of elliptical galaxies at high redshift to compare with the QSO LF, we can simply scale the present day luminosity function for elliptical galaxies in both luminosity and space density using *observed* or established properties of elliptical galaxies and their cores.

In a series of recent papers, we have shown that the predicted young core luminosity function is an excellent match to the observed luminosity function for QSOs in the redshift range from 2.0 to 2.9 (Boyle 1992; Terlevich 1992; Terlevich & Boyle 1993). Thus, **the young cores of ellipticals containing only 5 % of the total galactic mass are capable of producing the luminosity of even the most luminous QSOs.**

6. IRAS GALAXIES AS PROGENITORS OF QSOs

One important prediction of the Starburst model regards the properties of the progenitors of QSOs. As discussed in the second section of this paper, the HII and Seyfert 2 phases are associated with large amounts of dust. This is due not only to the dust present in any star formation region but also to the large amount of dust synthesized by the most massive stars during the η-Carinae phase before becoming WR stars. During this phase up to 1 $M_\odot$ of dust per evolved massive star may be injected into the core ISM, enshrouding most of the massive stars. Therefore, the emitted luminosity will be dominated by the far infra-red (FIR) luminosity and these systems will presumably be present in large numbers in the IRAS sample of Starbursts and Seyfert 2.

The HII and Seyfert 2 phase that precedes the QSO phase lasts 8×10^6 years, or about 1/10 of the duration of the QSO phase. During this early phase, the cluster luminosity is at its maximum, and, on average, about 4 times higher than during the QSO phase. The QSO progenitor should therefore be a luminous and short lived (short compared with the QSO life-time) FIR source. Comparative studies of the luminosity function of IRAS galaxies and QSOs should show if IRAS galaxies are, at a given epoch, about 4 times more luminous in bolometric units and about 10 times less frequent than QSOs. This simple prediction applies only to the case of a coeval population; systems where the star formation time scale is longer will show a mixture of all four phases at all times and will therefore probably look like a QSO for most of their bright phase.

7. CONCLUSIONS

Recent results on evolving young luminous compact SNR can explain a large number of the observed properties of the BLR of AGN with a minimum number of free parameters. If our hypothesis is correct it hould be possible to extend this simple model to explain the observed variability of Seyfert nuclei in the ptical, UV, and X-ray spectral range.

We suggest that perhaps most of the high redshift unresolved emission line objects found in optical surveys nd classified as QSOs due to the presence of broad permitted emission lines in their spectrum, are in fact the oung cores of elliptical galaxies forming in a single starburst most of their metal rich stellar population.

We are aware of the existence of strong radio emission and radio jets in a few (less than 10%) of the AGN ources. We also know about the X-ray variability and micro-variability detected in some Seyfert nuclei; all of hese events, as long as the energies involved remain within the range expected from a violent stellar burst and heir supernova output, deserve to be considered for an explanation within the starburst model for AGNs. The reliminary results are promissing, given the detailed agreement with the large majority of sources (see paper), and yet there still remain a wide number of possibilities to explore. These, to name a few, may relate to the nvironment of the nuclear starburst, and/or the detailed physics of remnants driven by fragmented ejecta, or he role played by the large population of pulsars, and the importance of high density toroidal and/or poloidal nagnetic fields in the cores of elliptical galaxies.

Although more work is needed, the research done so far indicates that the Starburst model, based in simple ssumptions, is potentially able to reproduce the main observed properties of radio quiet Active Galactic Nuclei.

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