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THE STARBURST MODEL FOR AGN: PAST, PRESENT, AND FUTURE

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RESUMEN

Han pasado once años desde que Terlevich y Melnick propusieron su modelo de AGN sin agujeros negros, una idea que desde entonces ha evolucionado a lo que hoy conocemos como el modelo de starburst para galaxias activas. Este modelo ha sido tema de discusión y polémica en la última década, con evidencias observacionales tanto a favor como en contra. Después de todos estos años, ¿podemos aclarar si los "starbursts" son responsables de la actividad en AGNs? En esta contribución intentamos responder a la pregunta, revisando las principales virtudes y problemas del modelo.

ABSTRACT

It is now eleven years since Terlevich & Melnick first proposed an 'AGN without black-holes' model, an idea which since then evolved into what is now called the starburst model for AGN. This model has been the subject of much debate in the last decade, with observational evidence both for and against it further fueling the controversy. Can we after all these years reach a veredictum on whether starbursts can power AGN? This contribution tries to answer this question reviewing the main achievements of the starburst model, its current status and future prospects.

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

1. INTRODUCTION

Probably the most extreme example of 'starburst activity in galaxies' occurs when a nuclear starburst behaves like an AGN. But is that possible? Can the basic properties of Active Galactic Nuclei be understood in terms of physical processes associated with a starburst? By the mid 80's the answer to this question was 'no', as there seemed to be no reasonable way to explain basic AGN properties such as variability, emission line ratios and widths in terms of stellar processes. The consensus then emerged that accretion onto a super-massive black hole is the ultimate source of energy in active galaxies, though it is fair to say that this consensus was at least partially established due to the lack of plausible alternative theories. Since then, Terlevich and collaborators, have given new breath to starburst-based models for AGN exploring new possibilities such as warmers and compact Supernova Remnants (cSNRs). There have been several reviews of the starburst model for AGN, such as those by Terlevich (1989, 1992, 1994), Filippenko (1992) and Heckman (1991). This review differs from the previous ones because it comes in a time when, curiously, though there have never been as much evidence for a connection between star-formation and activity, there are also new strong evidence for the existence of accretion disks and black holes in AGN, as the reader will realize browsing through this very volume. This may well be indicating that the answer to the AGN phenomenon lies with neither starbursts nor black-holes, but *both*, an idea which gathered some strength during this conference. It is, however, important to establish the virtues and limitations of both theories before reaching such a strong conclusion. In this paper I review the essential aspects of the starburst model for AGN, discussing which aspects of the activity phenomenon can be adequately understood in terms of the physics of starbursts and cSNRs, as well as properties which do not seem to fit in this framework.

2. OVERVIEW OF THE MODEL

The starburst model started with the idea that hot stars could power the ionization in narrow lined AGN, and gradually switched its focus to the phenomena associated with cSNRs in a nuclear starburst. In this section I briefly review the history model, indicating strong and weak points and updating it where necessary.

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2.1. Warmers

The official kick-off of the starburst model was given in 1985 by Terlevich & Melnick. They proposed a scenario in which the central ionizing source consists of a young, massive, metal-rich cluster containing 'warmers', extreme WR stars reaching temperatures of ~ 150 000 K. The existence of such stars was supported by stellar evolution calculations (e.g., Maeder & Meynet 1988) which showed that strong mass-loss could strip-off the outer layers of massive stars, exposing their hot interior. Terlevich & Melnick's calculations (later confirmed by Cid Fernandes et al. 1992 and Garcia-Vargas & Díaz 1992) showed that a cluster containing 'warmers' would have an ionizing spectrum hard enough to photoionize the surrounding gas to Narrow Line Region like conditions. Though a few warmers have been found (e.g., Dopita et al. 1990), by now it is clear that they are not as common as previously thought, most likely because the mass lost, during the evolution, forms an opaque atmosphere which effectively reduces the temperature of the star. In fact, updated spectral synthesis calculations using newer evolutionary tracks and appropriate stellar atmospheres for the WR phases show that the ionizing spectrum is more typical of H II regions than of AGN (e.g., Leitherer, Gruenwald, & Schmutz 1992). In summary, 'warmers' did not live up to be the long sought 'missing link between starbursts and AGN'. This is not to say that WR-stars have nothing to do with AGN. In fact, the existence of objects showing both AGN and WR features points to some sort of connection at least in some cases (see Conti 1993). It is nevertheless clear that a sound starburst model for AGN could not be based on the existence of warmers. Indeed, in the subsequent papers cSNRs (§ 2.3) have replaced warmers as the basic agent of activity, to the point that warmers are *not* a necessary ingredient of the model anymore.

2.2. Evolutionary Scheme

Terlevich, Melnick, & Moles (1987) considered the evolution of a metal-rich nuclear starburst, dividing it into four phases: (1) an initial H II region phase lasting for ~ 3 Myr, when all stars are in the main-sequence, (2) a phase from 3 to 4 Myr when the first warmers appear and the emission line spectrum changes to Seyfert 2 or LINER, (3) a phase from 4 to 8 Myr where warmers and OB stars still dominate the ionization but the cluster also contains type Ib SNe and red supergiants, and (4) a Seyfert 1 phase from 8 to 60 Myr, when cSNRs produce variability, ionization and broad lines. There are several reasons why this scheme should be revised, the first of which is that, as discussed above, warmers can almost certainly be ruled out as abundant sources of ionizing photons. Besides, we now know that, at least in some cases, the difference between Seyfert 2s and Seyfert 1s is not an evolutionary one, but an orientation effect. A revised evolutionary scheme would comprise only two phases: an initial H II region (or LINER, depending on the density and metallicity; Shields 1992; Filippenko & Terlevich 1992) phase lasting until the first cSNR appears at ~ 8 Myr and the nucleus turns into a Seyfert 1. During both phases the action of stellar winds and SNRs can drive a biconical outflow if the parent molecular cloud (the torus?) is flattened. This mechanism would naturally create the conditions postulated by the unified model. Seyfert 2s would then be simply edge-on Seyfert 1s. Some Seyfert 2s and LINERs could also be face-on low luminosity phase 2 systems, where the low SN rate ensures quiescent periods with little or no variability nor broad lines (Aretxaga & Terlevich 1994).

2.3. Compact Supernova Remnants

cSNRs are the key ingredient in the starburst model. They are in fact the only thing which set AGN-like starbursts apart from ordinary ones. In the context of the starburst model for AGN, cSNRs are responsible for the time variability, X-ray and radio emission, the BLR properties and the NLR ionization, as explained in the seminal paper by Terlevich et al. (1992). cSNRs are nothing but ordinary SNRs evolving in a dense circumstellar medium ($n_{CSM} > 10^6$ cm^{-3}). Density is the main parameter governing the evolution of the remnant, though metallicity and the detailed structure of ejecta and CSM also play a role. At such high densities cooling of the shocked material is very efficient and the remnant is capable of radiating away most of its kinetic energy in a few years. The structure and evolution of a cSNR is complex and has to be followed numerically, and hydro codes have only recently been adapted to work under such extreme conditions. The first simulations of cSNRs were those by Terlevich et al. (1992). More recent and detailed calculations can be found in Plewa (1995), Terlevich et al. (1995), and Cid Fernandes et al. (1996). The state of the art in numerical modeling of radiative shocks is reviewed in T. Plewa's contribution. To first order, the structure of a cSNR comprises 4 regions (see schemes in Terlevich et al. 1992 and Cid Fernandes & Terlevich 1994). From the inside out: (1) the unshocked, freely expanding ejecta, (2) shocked ejecta, (3) shocked CSM and (4) unperturbed CSM. Dense, cold, fast moving thin shells form behind both the forward and reverse shocks via catastrophic cooling. These two cold regions plus the unshocked ejecta are photoionized by the high energy photons emanating from the cooling regions, producing broad emission lines whose ratios, luminosities and widths are similar to those found in AGN. Though many details remain to be worked out, the cSNR model is definitely in the right track, as confirmed by the discovery of objects like SN 1987F (Filippenko 1989), with a spectrum so similar to that of AGN that led Filippenko to call it a 'Seyfert 1 impostor'. Besides, being fascinating objects by themselves, cSNRs are potentially the true missing link between starbursts and AGN. Whether or not they can explain AGN properties which have puzzled us for so long, there can be little doubt that a starburst whose SNe evolve into cSNRs will look like an AGN in many aspects. In my view, this has been already *proven* both theoretically, with the work described above, and empirically, with the discovery of 'Seyfert 1 impostors'. At this stage, I cannot help observing that, unlike the situation in AGN studies, the theory of cSNRs is parsecs ahead of observations. cSNR simulations have reached an unprecedent stage of refinement. We can, for instance, consider the detailed structure of both ejecta and CSM, as well as the effects of inhomogeneities on the evolution of the remnant. The theory here is really crying out to be tested. Detailed observations of cSNRs are badly needed not only to better guide the theory of radiative shocks but to strongly test the cSNR-AGN connection proposed by the starburst model.

2.4. Why High Density?

All that is required for a SN to become a cSNR is a dense CSM. Given this, a starburst will *certainly* present many AGN properties. But what generates such a high density? The historical explanation was based on the effects of metallicity (Terlevich & Melnick 1985; Terlevich, Melnick, & Moles 1987). The central regions of a galaxy, particularly early type ones, where most AGN are found, have an enhanced metallicity, which would enhance radiatively driven mass loss, creating both warmers and a dense CSM around the cSNR progenitor. This reasoning was used by Terlevich, Melnick, & Moles to explain the predominance of AGN at early Hubble types and starbursts at late types. Though metallicity certainly plays some role, the current view is that the ISM in a nuclear starburst is pressurized by stellar winds and SNRs. The high pressure confines the wind driven bubbles to small volumes, creating the conditions for SNe to become cSNRs (see J. Franco's contribution elsewhere in this volume). This, however, is probably not the only way to produce cSNRs, since objects like SN 1987F and SN 1988Z (Filippenko 1989; Stathakis & Sadler 1991) were found in regions showing no signs of particularly violent star-formation.

3. AGN PROPERTIES EXPLAINED BY THE MODEL

Having gone through the basics, I now briefly outline some of the AGN phenomenology which can be at least reasonably well understood in the framework of the starburst model.

3.1. BLR Properties

That cSNRs can have emission line regions aking to those of Seyfert 1 was already realized by Fransson (1984) in his early study of SN-CSM interaction. Indeed, the combined hydrodynamics + photoionization calculations of Terlevich et al. (1992) demonstrated that cSNRs do at least as well as canonical models in reproducing the BLR line ratios. Furthermore, the different photoionized regions (the two thin shell associated with the forward and reverse shocks plus the ejecta) explain the existence of high and low ionization line regions (e.g., Collin-Souffrin et al. 1988). Reproducing the basic BLR properties with a *physical* model, as opposed to an *ad hoc* model such as a central ionizing source plus an arbitrary distribution of clouds, is one of the main achievements of the starburst model. Though the velocities and luminosities of the line emitting regions in cSNRs are similar to those in the BLR, detailed emission line profile calculations proved to be more complicated than initially thought (Cid Fernandes & Terlevich 1994; Cid Fernandes 1995). The complications arise because the line emitting shells are thought to be optically thick, but geometrically too thin to be modeled with the Sobolev approximation. In this situation, calculations are very sensitive to the detailed shape of the shells, which is likely to be distorted by instabilities. Though the theory here still needs work, one can always resort to the empirical argument that *observed* profiles in cSNRs such as SN 1987F and SN 1988Z would probably go un-noticed if put among a gallery of AGN profiles. A further complication is that, discounting low luminosity systems ($M_B \gtrsim$-20), chances are that we seldom observe isolated cSNRs in AGN. Interestingly, computations of the line profiles for multi-cSNR systems yielded more robust results than for individual cSNRs. Effects such as the line width-luminosity correlation and the centrally depressed $H\beta/H\alpha$ profile ratio can be readily understood in the model.

3.2. Optical-UV Variability and the Origin of the Lag

Most of the recent interest in AGN variability has been on the time-lag between continuum and emission line variations, with intensive monitoring campaigns designed to reconstruct the BLR geometry using echo-mapping techniques. In the starburst model for AGN the lag is *not* due to reverberation, but due to the hydrodynamical effects associated with thin shell formation behind radiative shocks (Terlevich et al. 1995; Plewa 1995). As the shocked material begins to cool in the processes leading to shell formation, lots of radiation are released, producing a continuum burst. Eventually the cold gas collapses onto a thin shell, but this only happens some time after the maximum in the continuum, explaining the origin of the lag. As the continuum burst fades and the shell density increases, the ionization parameter goes down, explaining why low ionization lines take longer to respond to continuum variations. After shell formation, shock oscillations produce further variations, but this time the shell is already formed and there should be little or no lag, explaining the puzzling observation that some events show essentially no lag (e.g., Clavel et al. 1991). This elegant, albeit controversial interpretation, illustrates the richness of phenomena associated with cSNRs and radiative shocks in general. The optical-UV continuum variability of starburst powered AGN is reviewed in I. Aretxaga's contribution, where the reader can find how properties such as the light curve statistics of Seyfert 1s, the anti-correlation between variability and luminosity and the Structure Function of QSOs are explained in the starburst model.

3.3. QSO Luminosity Function

Terlevich & Boyle (1993) carried out the interesting exercise of evolving the stars in the core of present day elliptical galaxies back in time (see also Terlevich 1992 and Boyle 1994). With simple assumptions they were able to reproduce the shape, amplitude and evolution of the QSO luminosity function, supporting not only the starburst model version of QSOs as young/primeval galaxies but also galaxy formation models which indicate that giant ellipticals have gone through a period of intense star-forming activity around $z \gtrsim 2$. (See Heckman 1994 and Terlevich 1994 for an interesting debate on this volume).

3.4. Etcetera

The points above are those which have been studied in more detail, but there are other AGN properties which can also be understood in the framework of the starburst model. These include (in varying stages of development): the Ca II absorption triplet (Terlevich, Díaz, & Terlevich 1990), the spectral energy distribution (Terlevich 1990), radio emission and variability (Colina 1993), the nature of strong Fe II emitters, size of the cluster and mass segregation (Terlevich 1994), effects of magnetic fields (Różyczka & Tenorio-Tagle 1995) and X-ray features such as the warm-absorber, cold reflector and high-energy cut-off.

4. AGN PROPERTIES NOT EXPLAINED BY THE MODEL

Despite this impressive list of explainable properties, the starburst model has from its early days been subjected to criticism from several fronts. The similarities between radio quiet and radio loud AGN, for instance have always been a matter of worry, since radio loud objects have from the outset been excluded by the model Other unresolved issues include micro-variability, and the absence of a Lyman edge and stellar features in the UV. However, rapid X-ray variability and the recently discovered broad Fe lines are, in my view, the most serious difficulties currently faced by the model. Rapid X-ray variability has always been seen as a serious problem for non-black hole models for AGN, a point not so much based on theory, but on the fact that galactic black-hole candidates (Cygnus X-1 being the classic example) also show rapid variability (see Mushotsky, Done, & Pounds 1993). Similarity arguments, however, have to be taken with care, since on optical wavelengths (at least) cSNRs are much more AGN-like than galactic black holes. Furthermore, gamma ray observations are revealing a clear difference between the high energy spectra of Cygnus X-1, which goes well into the MeV range, and that of radio-quiet AGN, which turns-over at about 100 KeV and cuts off at a few hundred KeV (A. Carramiñana priv. comm.; McConnell et al. 1994; Warwick et al. 1996). (See also Kinney 1994 for a comparison between stellar accretion disk systems and AGN.) In any case, it is difficult to see how cSNRs could produce strong rapid X-ray variability. The interaction of SN fragments with the dense, thin shells in cSNRs can give rise to rapid X-ray flares, but, as discussed by Cid Fernandes et al. (1996), the physical conditions required to model AGN-like flares quantitatively are too extreme. This, however, has yet to be verified with X-ray monitoring of cSNRs—the fact that we do not know how to produce strong, rapid variability does not mean that they do not have it! The discovery of an extremely broad ($\sim c/3$) Fe line in MGC 6-30-15 (Tanaka et al. al 1995), a feature now detected in many other Seyfert 1s (see R. Mushotsky contribution), brought further problems for the starburst model. Besides being very difficult to see how such a wide line could be produced in cSNRs, the observed profile is remarkably well fit by a relativistic accretion disk model. Further compelling evidence for a disk surrounding a compact super-massive object came with the water maser observations of NGC 4258 by Miyoshi et al. (1995).

5. DISCUSSION: STARBURSTS, BLACK-HOLES OR BOTH?

All in all, the starburst model proved capable of explaining several, though not all, AGN properties. What makes the model so attractive is its deductive character, deriving observables out of physics instead of parameters. Though the numerical balance of evidence for and against may favor the starburst model, a single unexplained observation is enough to put any model in trouble. When an astrophysical model is in trouble we either (1) drop it altogether, (2) modify/fix it or (3) opt to say it does not apply to all objects. As already said above, starbursts containing cSNRs would certainly look like AGN in many ways, so there must be some, maybe many objects of this kind in AGN lists. In this sense, at least, ruling out a starburst origin for the activity in galactic nuclei is not a sensible alternative. The choice therefore has to be between fixing the model or restricting its applicability to a sub-set of the AGN family. The easiest way to account for rapid X-ray variability, broad iron line and radio loud objects would be to go for a hybrid black-hole + starburst scenario. One version of such a model is that of J. Perry and collaborators, reviewed elsewhere in this volume. Naively, one could think that combining a "Terlevich-type" of starburst with a black-hole would fix the problems with X-rays, with stars and cSNRs still responsible for the activity at lower energies. While this might work in some cases, my view is that such a scheme does not provide a natural explanation for the correlations between high and low energy properties of AGN, one example being the correlation between X-ray and Balmer line luminosities (e.g., Ward et al. 1988). Such correlations indicate that the low and high energy photons somehow know about each other, something which would be difficult to understand if they originate from very different phenomena. It is therefore not obvious that a simple combination of the canonical and starburst paradigms is the answer. I conclude that, to the disgust of purists, the evidence seems to be pointing to two kinds of objects: starburst and accretion-powered AGN. This is not a new idea, as many of us always suspected that AGN constitute a mixed bag. Distinguishing between these two possibilities has been a central theme in the starburst × monster debate (see Filippenko et al. 1993). At this stage, detection of strong, rapid X-ray variability and broad Fe lines are the best indication of the existence an accretion-disk in AGN. Experiments to resolve the small but extended nucleus predicted by the starburst model will eventually provide a more conclusive method to discriminate starburst from accretion-powered AGN. Going back to our original question, can we after all these years reach a veredictum on whether starbursts can power AGN? Given the advances on cSNR theory and the discovery of objects like SN 1987F and SN 1988Z, we can safely say that yes, starbursts *can* power AGN. At the same time, recent discoveries have put the standard accretion-disk model on firm ground. Whatever the final answer to this cosmic puzzle is, it is clear that while we digest this apparent conflict, much can be learned observing cSNRs. A fundamental aspect which differentiates the starburst model from black-hole and hybrid models is that many of its predictions can be tested *outside* AGN. Galactic black-hole candidates are about the closest one can get to an AGN-like engine, but applying the knowledge of such systems to AGN involves an uncomfortable leap of several factors of 10. cSNRs, on the contrary, are expected and observed to be similar to those inferred to exist in the cores of massive starburst-powered AGN. They therefore provide a unique laboratory to strongly test the starburst-AGN connection and to help us solve this yet unfinished debate.

REFERENCES

Aretxaga, I., & Terlevich, R. 1994, MNRAS, 269, 462
Boyle, B. J. 1994, in Violent Star Formation: From 30Dor to QSOs, ed. G. Tenorio-Tale (Cambridge: Cambridge Univ. Press), 413
Cid Fernandes, R. 1995, Ph.D. Thesis, University of Cambridge (available in the WWW: http://if.ufrgs.br/~cid)
Cid Fernandes, R., Dottori, H., Gruenwald, R., & Viegas, S. 1992, MNRAS, 255, 165.
Cid Fernandes, R., & Terlevich, R. 1994, in Violent Star Formation: From 30Dor to QSOs, ed. G. Tenorio-Tale (Cambridge: Cambridge Univ. Press), 365
Cid Fernandes, R., Plewa, T., Różyczka, M., Franco, J., Tenorio-Tagle, G., Terlevich, R., & Miller, W., 1996, MNRAS, in press
Clavel, J. et al. 1991, ApJ, 366, 64

Colina, L. 1993, Ap&SS, 205, 99

Collin-Souffrin, S., Dyson, J. E., McDowel, J. C., & Perry, J. J. 1988, MNRAS, 232, 539

Conti, P. 1993, in The Nearest Active Galaxies, ed. J. Beckman, L. Colina, & H. Netzer (Spain: Nuevas Tendencias, CSIS), 258

Dopita, M., Lozinskaya, T., McGregor, P., & Rawlings, S. 1990, ApJ, 351, 563

Filippenko, A. V. 1989, AJ, 97, 726

____________. 1992, in Physics of Active Galactic Nuclei, ed. S. Wagner & W. Duschl (Berlin: Springer-Verlag), 345

Filippenko, A. V., & Terlevich, R. 1992, ApJ, 397, L79

Filippenko, A. V., Conti, P., Genzel, R., Heckman, T., Mushotzky, R., & Terlevich R. 1993, in The Nearest Active Galaxies, ed. J. Beckman, L. Colina, & H. Netzer (Spain: Nuevas Tendencias, CSIS), 257

Fransson, C. 1984, A&A, 133, 264

Garcia-Vargas, M. L., Díaz, A., Terlevich, E., & Terlevich R. 1992, in ASP Conf. Ser. Vol. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 197

Heckman, T. 1991, in Massive Stars in Starburst Galaxies, ed. C. Leitherer, N. Walborn, T. Heckman, & C. Norman (Cambridge: Cambridge Univ. Press), 289

____________ 1994, in Mass-Transfer Induced Activity in Galaxies, ed. I. Shlosman (Cambridge: Cambridge Univ. Press), 234

Kinney, A. 1994, in ASP Conf. Ser. Vol. 54, The First Mount Stromlo Symposium: The Physics of Active Galaxies, ed. G. V. Bicknell, M. A. Dopita, & P. J. Quinn (San Francisco: ASP), 61

Leitherer, C., Gruenwald, R. & Schmutz, W. 1992, in Physics of Nearby Galaxies, ed. T. Thuan, C. Balkowski, & J. Tran Tranh (Paris: Editions Frontières)

Maeder, A., & Meynet, G. 1988, A&AS, 76, 411

McConnel, M., Forrest, D., Ryan, J., Collmar, W., Schoenfelder, V., Steinle, H., Strong, A., Van Dijk, R., Hermsen, W., & Bennet, K. 1994, ApJ, 424, 933

Mushotzky, R. F., Done, C., & Pounds, K. A. 1993, ARA&A, 31, 717

Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature 373, 127

Plewa, T. 1995, MNRAS, 275, 143

Różyczka, M. & Tenorio-Tagle, G., 1995, MNRAS, 272, 198

Shields, J. 1992, ApJ, 399, L27

Stathakis, R. A., & Sadler, E. M. 1991, MNRAS, 250, 786

Tanaka et al. 1995, Nature, 375, 659

Terlevich, E., Díaz, A., & Terlevich, R. 1990, MNRAS, 242, 271

Terlevich, R. 1989, in Evolutionary Phenomena in Galaxies, ed. J. E. Beckman & B. E. Pagel (Cambridge: Cambridge Univ. Press), 149

____________. 1990, in Windows on Galaxies, ed. G. Fabbiano, J. Gallagher, & A. Renzini (Dordrecht: Kluwer), 87

____________. 1992, in ASP Conf. Ser. Vol. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko (San Francisco: ASP), 133

____________. 1994, in Circumstellar Media in the Late Stages of Stellar Evolution, ed. R. E. S. Clegg, I. R. Stevens, & W. P. S. Meikle (Cambridge: Cambridge Univ. Press), 153

Terlevich, R., & Boyle, B. J. 1993, MNRAS, 262, 491

Terlevich, R., & Melnick, J. 1985, MNRAS, 213, 841

Terlevich, R., Melnick, J. & Moles, M. 1987, in Observational Evidence for Activity in Galaxies, ed. E. Khachikian, K. Fricke, & J. Melnick (Dordrecht: Reidel), 499

Terlevich, R., Tenorio-Tagle, G., Franco, J., & Melnick, J. 1992, MNRAS, 255, 713

Terlevich, R., Tenorio-Tagle, G., Franco, J., Różyczka, M., & Melnick, J. 1995, MNRAS, 272, 192

Ward, M., Done, C., Fabian, A., Tennant, A., & Shafer, R. 1988, ApJ, 324, 767

Warwick, R. S. et al. 1996, ApJ, 470, 349