Star Formation and Abundances in S0 Galaxies

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Abstract. A significant number of S0 galaxies with a detectable ISM show some level of on-going massive-star formation activity in the form of visible H II Regions. A rich ISM, however, does not guarantee star formation: a significant number of relatively gas-rich S0s have no detectable H II regions down to the level of regions ionized by single O stars (e.g., Orion-like H II regions). The Hα luminosities of star-forming S0s imply global star formation rates as much as 2–3 orders of magnitude lower than in spirals. Spectroscopy of the bright H II regions in a few of the star-forming S0s studied thus far reveal solar gas-phase oxygen abundances. In general, S0s fall onto the general trends of O/H with galaxy luminosity and Hubble Type seen for Spirals and Irregulars, and have O/H abundances typical of spirals of similar total stellar luminosity. The implications are that S0s appear to be the low end of the Hubble Sequence of spirals, and that their interstellar gas is primarily internal in origin. The surprise is that two counter-rotating S0s, which show direct evidence of a massive infall of gas and stars, also follow these trends.

1. Introduction: The S0 Problem

The S0 galaxy class was invented by Hubble (1936) to fill a transitional gap between ellipticals and spirals in his original morphological sequence (Hubble 1926). He proposed it as a way to “include objects later than E7 but with no trace of spiral structure” within his system, but in 1936 he had no observational evidence for the class. It was not until the 1950s that definitive examples were identified from photographic surveys, and the first systematic description of S0s in the literature was by Sandage (1961) in The Hubble Atlas of Galaxies.

Why did it take so long? One of the reasons is that in some sense S0 galaxies are classified not so much by what they are, as by what they are not. As a result, S0s are notoriously difficult to classify consistently (e.g., Knapp et al. 1989). Once you divide non-irregular galaxies between ellipticals and spirals, S0s are what are leftover, and the fine details of which category these belong in becomes strongly subject to the quality of the observational material. In selecting a sample for study, one invariably encounters objects that on close inspection have no business being on the observing list (see Eder 1990 and Pogge & Eskridge 1993 for examples of what can turn up in CCD imaging studies).

Despite these difficulties, a general picture of their basic properties has emerged. S0s are galaxies with massive bulges and weak disks without spiral
structure, and dominated by an old stellar population. They have ISMs comprised of a small quantity of cool gas (atomic and molecular) and a small amount of dust, and can occasionally have a substantial hot ISM. The strongest departure from the traditional picture is the recognition that a good fraction of all bona-fide S0 galaxies have a reasonably substantial interstellar medium.

Of special concern to us here are the cool components of the ISM: HI, H$_2$ (CO), and dust (FIR). From surveys of early-type galaxies (Bregman et al. 1992; Hogg et al. 1993, and references therein), the state of our knowledge of the cool ISM in S0s may be summarized as follows:

**HI 21-cm:** Between 30–40% of S0s are detected, with HI masses in the range of $10^7 \lesssim M_{HI} \lesssim 10^{10} M_\odot$.

**H$_2$ (CO):** The $^{12}$CO detection rate for S0s is $\sim 25\%$, with inferred H$_2$ masses also in the range of $10^7 \lesssim M_{H2} \lesssim 10^{10} M_\odot$.

**Dust (FIR):** The FIR (60 and 100$\mu$m) detection rate for S0s is $\sim 40 − 60\%$, implying dust masses in the range of $10^4 \lesssim M_{dust} \lesssim 10^7 M_\odot$ and typical dust/gas ratios.

In general, the cool ISM properties of S0 galaxies lie intermediate between those of Ellipticals and Spirals (Hogg et al. 1993).

While the ISMs of S0 galaxies are reduced in scale relative to spirals, they seem to have the same basic components in roughly similar proportions. This has led to the question of whether there is enough interstellar material in the right places for S0s to form new stars in the present day. This paper reviews what has been learned about on-going massive star formation in S0 galaxies, and what can be learned about the ISM in these galaxies from the properties of the HII regions, especially the gas-phase abundances. We compare the star formation properties of S0s with normal spirals, and conclude with some questions for further study.

### 2. Present-Day Star Formation in S0s

The most direct way to ask whether S0 galaxies are forming stars now is to search for H$\alpha$ emission from HII regions using narrow-band imaging. There have been two main studies to date that we will focus on: the Lick Survey of Pogge & Eskridge (1993, henceforth PE93), and the CTIO study of Caldwell, Kennicutt, & Schommer (1994, henceforth CKS).

PE93 (also Pogge & Eskridge 1987) surveyed 40 gas-rich S0 galaxies using on-band/off-band filter imaging techniques. This work used a 1-m telescope with 75Å bandpass filters in redshifted H$\alpha$+[N II] emission-line bands and adjacent emission-free continuum bands. Of the 40 galaxies in their combined sample, 8 were rejected as mis-identified (most were misclassified irregulars that look lenticular on POSS plates).

CKS studied 8 S0 galaxies using Fabry-Perot imaging on the CTIO 4-m telescope. The Fabry-Perot etalon had a very narrow bandpass (2.4Å FWHM), delivering roughly 10-times the sensitivity to faint emission against the bright galaxy background of the filter imaging used by PE93. This allowed the detection of fainter HII regions, and for much deeper upper limits on non-detections.
Combining the results of these studies and taking account of interlopers and overlaps, of the 40 S0 galaxies studied, 18 show clear evidence of significant populations of disk H II regions. The H II regions are primarily distributed into thin rings (some appearing as tightly wound spiral arms), with a range of galactocentric radii from kiloparsec-scale “nuclear rings” to “outer” rings of 10–20 kpc diameter. The remaining 22 S0 galaxies have no disk H II regions, with upper limits such that we should have detected single H II regions powered by a single O5 star if present. In CKS’s F-P study, the limits were very low, such that they could detect an H II region as faint as the Orion Nebula if present. Faint diffuse disk emission and nuclear emission-line regions are also seen in some of the galaxies upper limits, but nothing identifiable as a discrete H II region.

The distribution of integrated Hα luminosities for these galaxies is shown in Figure 1, along with the upper limits for the combined data sets (two of CKS’s galaxies are in common with ours, and we adopt their values). The upper panel shows the S0s, while the lower panels shows the data for Spiral galaxies studied by Kennicutt & Kent (1983). The luminosities of single H II regions (one O5 star and Orion) are indicated in the lower panel, along with the luminosity of the brightest planetary nebulae (taken from CKS). On average, the global star formation intensity in these galaxies is lower than in spiral galaxies by about a factor of 10, with the faintest extending to 2–3 orders of magnitude below spirals. To get some feel for how low it gets, the three S0 galaxies detected by...
CKS each had ~15 H II regions, with individual regions as faint or fainter than the Orion Nebula.

As CKS have correctly pointed out, in many cases our PE93 upper limits would not have permitted us to detect some of the faintest H II regions detected by their F-P study. Unfortunately, the only two galaxies we had in common were non-detections for both studies, so we cannot assess how much, if any, one should modify the non-detections reported by us. Still, even with these caveats in mind, it is clear that there exists a significant population of S0 galaxies with no star formation down to very faint limits.

Why the strong differences between star-forming and quiescent S0s? One interpretation (close to that discussed by CKS) is that star formation can proceed all the way down to zero with no minimum cutoff. What one is then seeing in the S0 galaxy population is a steady fading of star formation from a previous active state, active in this case being at the level seen in Sa galaxies. Indeed, during its “active” state, the galaxy would probably be classified as Sa instead of S0. Another possibility (discussed by PE93) is that the appearance of the HII regions in rings is strongly suggestive that the same kinds of dynamical threshold effects that mediate the rate of global star formation in spirals (Kennicutt 1988) is operating in the S0s. The S0s straddle the threshold for triggering star formation, and so galaxies with similar general properties and ISM masses (on average) can have radically different star formation properties.

At issue is whether there is a lower-limit to the star formation rate in S0s or whether it just fades away. A central problem is that neither observational study is on firm statistical grounds. Indeed, both studies have made only a detailed reconnaissance of the problem to establish both the commonality of star formation in S0s and the lower limits of its intensity. What is needed is a study undertaken with a carefully selected sample of field S0s (to avoid the considerable influence of the hot intra-cluster environment), and with careful attention to the problems of assessing the detection limits.

3. H II Region Abundances

Having established that at least some S0s have H II regions, what else can be learned from the H II Regions themselves?

The gas-phase abundances of the elements derived from H II regions provide essential data on the origin and evolution of the ISM in S0s. If the ISM is derived primarily by accretion (infall) of new gas, then with typical hydrogen (H I+H$_2$) masses of order $10^{8-9} M_\odot$, the most likely donors are gas-rich dwarfs or small intergalactic gas clouds. The abundances of such objects are observed to be significantly sub-solar (e.g., Skillman et al. 1989). Even if the infalling material were adding to a small amount of enriched intrinsic ISM gas shed by evolving stars, the gas-phase abundances should still be significantly diluted compared to the inferred stellar abundances.

On the other hand, if S0s are capable of replenishing their ISMs via mass loss from evolved stars (AGB stars and PNe) and SNIa, one expects solar or greater gas-phase abundances as is seen in the donor stars. In a classic computation, Faber & Gallagher (1976) argued that a typical S0 or E galaxy could build a substantial ISM in the mass ranges we are seeing in a few billion years.
To date, we have obtained spectra of sufficient quality to estimate extinctions, densities, and gas-phase oxygen abundances in 16 H II regions in six S0 galaxies. Because none of the H II regions had detectable [O III]λ4363 Å emission, we estimated O/H abundances in these H II regions using the $R_{23}$ method of Edmunds & Pagel (1984) and adopting the calibration of Dopita & Evans (1986) following Oey & Kennicutt (1993). We find that all of the H II regions have roughly solar O/H abundances, with a range between 0.8 and 2 solar and a median O/H of 1.4 solar, adopting the solar value of $12 + \log(O/H) = 8.93$ (Anders & Grevesse 1989). These values have a systematic uncertainty of 0.2 dex for the absolute calibration (e.g., Oey & Kennicutt 1993).

Figure 2 shows a comparison of our S0 galaxy H II regions with a sample of Sa galaxy H II regions observed by Oey & Kennicutt (1993) and H II regions in late-type spirals by McCall, Rybski, & Shields (1985). The S0 galaxy H II regions most resemble the Sa galaxies in their abundances, and on average reside in the metal-rich part of the range seen in late-type spirals. In general, the metallicities of the S0 galaxy H II regions do not resemble those of gas-rich dwarf irregulars, which range from a few percent of solar up to about 0.5 solar for the most massive (Skillman et al. 1989).
4. S0s and the Hubble Sequence

The star formation and H II region properties of S0 galaxies appear remarkably normal when placed among the rest of the sequence of spiral galaxies. As noted above, S0 galaxies appear to continue the general trend of decreasing star-formation rate with earlier Hubble Type observed by Kennicutt & Kent (1983), extending to the lowest instantaneous SFRs measured (CKS).

![Figure 3. Correlation of 12+log(O/H) with Hubble Type (top) and total Luminosity (bottom) for S0 through Irr Galaxies.](image)

Among spirals and irregular, there is a clear trend of decreasing oxygen abundance (O/H) with both later Hubble Type and decreasing luminosity (e.g., Roberts & Haynes 1994; Garnett & Shields 1987; Skillman, Kennicutt, & Hodge 1989). If we add our S0 galaxy results to the correlation diagrams plotted by Roberts & Haynes (1994) for Irr through Sa galaxies (Figure 3), we find that the S0s fit onto the observed trends. Thus the metallicities that we observe for S0 galaxy H II regions are typical for galaxies of their luminosity, and continue the observed trend with Hubble Type. If the ISM in S0s was primarily external in origin, due to recent infall of gas-rich dwarfs, we would have expected to see systematically lower O/H abundances than predicted from the trends for the galaxy luminosities, with a greater overall dispersion. The data therefore suggest that S0s are the lower end of the Hubble Sequence of Spirals, without having to invoke recent infall to explain their interstellar gas or star formation properties.
5. Counter-rotating Disks: A Conundrum?

If only it were so simple. Two of the six galaxies discussed in the previous section, NGC 4138 and NGC 3593 are examples of S0/Sa galaxies with counter-rotating disks of stars and gas (NGC 4138, Jore et al. 1996; NGC 3593, Bertola et al. 1996). In both, the H II region rings are apparently counter-rotating. The model for the formation of such structures, by the slow retrograde accretion of a gas-rich dwarf galaxy (e.g., Thakar & Ryden 1996; Thakar et al. 1997), would suggest that the metallicities should be as low as in the putative donors. Instead, we find metallicities of 1.7 and 1.5 times solar in NGC 4138 and NGC 3593, respectively.

Further, both galaxies are morphologically undisturbed. The ring of H II regions in NGC 4138 is perfectly aligned with the stellar light in visible and near-IR images (Figure 4). The same is true of NGC 3593 (Corsini et al. 1998, also Pizzella et al., these proceedings). There is nothing in their outward appearance to suggest they are the sites of past minor mergers, even though there is strong dynamical evidence of just such events. What is going on? Why are these structures both apparently relaxed and metal rich?

One possibility is that the infall/merger event that gave rise to the counter-rotating component occurred a long time ago, and formed a structure that can be stable for the lifetime of the galaxy. This would give it enough time to self-enrich the gas compared to the original abundances of the donor. Dynamical evidence of a merger, however minor, does not necessarily imply that it happened yesterday (i.e., that such structures are “smoking guns”; the gun may have cooled and the smoke cleared a long time ago). In particular, current models of hierarchical galaxy formation suggest that merging among galaxies was much more common in the past, and it is plausible that what we are seeing today is but a relict of the events that made these galaxies S0s (e.g., Bekki 1998). The fact that these two galaxies are morphologically undisturbed and otherwise non-descript argues that we need to look more closely at the longevity issue.

6. Summary and Future Directions

The star formation properties of S0 galaxies may be summarized as follows:

- A significant population of S0 galaxies is actively forming stars, while a similar population is quiescent down to the lowest measurable levels.
- In the star-forming S0s, the star formation rate is on average 10–100 times lower than in spirals, and, in a couple of systems, it is as much as ∼ 1000 times lower.
- The H II regions have solar or greater gas-phase oxygen abundances that are well within the normal range for spiral galaxies of similar luminosity.

In general, the trends of global star-formation rate and O/H abundances are consistent with S0 galaxies populating the low end of the Hubble Sequence of Spirals; there is no obvious discontinuity of properties from Sd through S0. Whatever the origin and subsequent evolution of the ISM is S0s (at least in the field), it is the same as in spirals, only there is less of it. A number of interesting questions are raised by these results:
Figure 4. $\mathrm{H\alpha} + \mathrm{[N\,II]}$ emission image of NGC 4138 with H-band (1.6\,$\mu$m) contours superimposed.

1. Is there a strong lower cutoff in star formation in S0s, or does star formation just fade away? Is the apparent cutoff a function of the detection limits? It is not simply a matter of gas content, since they are roughly similar in the star-forming and quiescent galaxies. Perhaps it is not how much gas a galaxy has so much as where it is and what form it is in (atomic or molecular) that matters. Until there are systematic studies of statistically well-defined samples with good HI and CO mapping (and not just reconnaissance), we will not be able to resolve this question.

2. How does the H II region luminosity function for star-forming S0s compare to that of later-type spirals? This is essentially unexplored territory, but would go a long way towards learning whether the global star formation process is proceeding differently than in spirals (cf. the work of Caldwell et al. 1991 on Sa galaxies). It is clear from the work surveying for H II
regions that the challenge is not just to find H II regions, but to find enough of them faint enough to build a luminosity function.

3. Why are two S0 galaxies with counter-rotating gas and stellar disks, the most obvious examples of galaxies that have experience substantial infall of interstellar material, more metal rich by an order of magnitude than their most likely donor population? Is this a fluke or a generic property of S0 galaxies with counter-rotating systems?

Finally, what are S0 galaxies? It has been suggested that if they have detectable star formation, they are not S0s. However, it is dangerous to base the classification on parameters that are critically dependent on the observation conditions (cf. CKS’s discussion along these lines). Star formation isn’t part of the classification criteria per se, although some prominent features of spirals are a consequence of star formation activity (e.g., the high contrast of spiral arms on blue photographic plates). In general, it is both unwise and contrary to the spirit of the morphological classification system to attempt to impose secondary physical criteria on any particular subclass. In the end, the only honest answer to the question of what are S0 galaxies is: we don’t know, but it looks as if we’re on the road to starting to learn how to ask the right questions that will lead to more satisfying answers.

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