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Constraints on the primordial helium abundance from the optical emission spectra of dwarf galaxies

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At present, the best estimate of the primordial helium abundance (Y_p) comes from helium abundances that have been derived from the emission spectra of dwarf galaxies. The *mean* Y_p deduced from the abundances in the 26 best observed dwarf galaxies is *ca.* 0.24. Individual galaxies may show a somewhat smaller Y_p (*ca.* 0.22) but the errors are uncertain and confirming observations are needed. It is important to search for more dwarf galaxies like IZw18 (with very low metal abundances) for further determinations of helium abundance.

1. Introduction

The primordial mass fraction of helium (Y_p) that was made in the Big Bang is currently considered to be a very significant observable quantity (Olive *et al.* 1981; Stecker 1980). The observational problem is to determine both the present mass fraction of helium (Y) in an astronomical source and also that part (ΔY) of that fraction that has been produced by stellar nucleogenesis since the Big Bang. We here review the best method yet devised for finding Y_p and comment on the sources of error and possible hopes for improving the accuracy.

Observations of the Sun and stars do not currently yield accurate values of Y_p, even though rather small error estimates are sometimes quoted (Olive *et al.* 1981; Serrano & Peimbert 1981). Some methods involve stellar spectra; others involve colours, magnitudes and masses; most are either indirect or imprecise, with complicated theoretical underpinning. Extreme population II stars would otherwise be very useful for determining Y_p because they have very low metal abundances and so their ΔY correction must be quite small.

The helium abundance is best measured from certain optical or radio emission lines produced in ionized interstellar gas. Since these lines come mostly from recombination events, the He/H line-intensity ratios measure relative numbers of coexisting *ionized* He and H atoms. This determination of abundance is theoretically direct and also insensitive to the gas temperatures and densities. The use of radio-recombination lines is interesting (Thum 1980) but has two drawbacks. First, because of instrumental sensitivity, its use has been confined to the relatively metal-rich gas in our own galaxy, for which the ΔY correction is large. Second, many radio-observed regions are thought to have significant amounts of unobservable non-ionized helium coexisting with the ionized hydrogen.

Oxygen is representative of heavy elements whose origin can be assumed to be entirely post-primordial; further, its abundance can be readily estimated from the optical emission spectrum of an H II region. Thus, we may hope to deduce ΔY by finding a linear correlation between the oxygen and helium abundances, and then extrapolating to zero oxygen abundance.

This approach has been adopted by various authors for discussing H II regions in our galaxy, the Magellanic Clouds and other nearby galaxies (Peimbert & Torres-Peimbert 1974, 1976; Lequeux *et al.* 1979; French 1980; Serrano & Peimbert 1981). Unfortunately the method is not very trustworthy if the ΔY correction is significant. The empirically determined values of the 'enrichment ratio', $\Delta Y/\Delta Z(\mathrm{O})$, span a considerable range. This range itself causes a 5% relative uncertainty in Y_p if the abundances are derived from H II regions as metal-rich as those in the Large Magellanic Clouds. Although the estimated $\Delta Y/\Delta Z(\mathrm{O})$ values seem theoretically plausible (Serrano & Peimbert 1981; Chiosi & Matteucci 1982), they depend upon the distribution of masses of the stars responsible for the nucleosynthesis. This enrichment ratio will therefore depend upon both the age and initial mass distribution and so will vary from source to source; moreover, for all we know, the ratio may not be constant for very low oxygen abundances. It may be relevant to note that the Crab supernova ejected helium but virtually no extra synthesized oxygen.

2. The derivation of Y_p by using dwarf galaxies

We are therefore driven to prefer H II regions, whose compositions (judged by their oxygen abundances) require us to use the smallest possible ΔY corrections. Enrichment appears to correlate with galaxy mass (see Kinman & Davidson 1981), so the best sources are emission-like dwarf galaxies with weak stellar continua such as IZw18 (Sargent & Searle 1970). The gas in these galaxies (which are ionized by young hot stars) has only been mildly contaminated with the products of nucleosynthesis; the oxygen abundances are between one-tenth and one-fortieth of that of the Sun. In this case, the ΔY corrections are small and these sources give us the lowest accessible upper limits to Y_p. Kunth (1981) has discussed in detail the various causes of uncertainty in estimates of Y_p. Fortunately, compared with most other emission-line sources, these dwarf galaxies have several characteristics that are favourable for helium abundance estimates.

1. The exciting stars are hot. Therefore, in the relevant optical wavebands, the emission lines are brighter than the stellar continua. This minimizes the effect of underlying stellar absorption lines that coincide with the emission lines. The effect is worse for the He I $\lambda 4471$ line; but if both this and the He I $\lambda 5876$ line are observed, one can use the known theoretical ratio of these as emission lines to make an appropriate (small) correction.

2. The relevant gas densities are low. Consequently, the effects of collisional excitation and the self-absorption of the helium lines result in very small corrections.

3. These objects do not have strong [N II] emission. The nitrogen is therefore mostly N^{2+} rather than N^{+}. This implies that almost all of the helium is ionized and so the unobservable neutral helium is scarce and needs only a small correction.

4. The gas is relatively hot because heavy-element cooling agents like oxygen are scarce. Moderately high temperatures tend to simplify the analysis for our abundance determinations.

Altogether, the above effects probably contribute a relatively uncertainty of *ca.* 3% in Y_p (Kunth appears to be more optimistic). Uncertainties in the correction for interstellar extinction are comparable, at least in some cases.

3. The present best estimate of Y_p

Recently a substantial number of estimates of helium and oxygen abundances in dwarf galaxies have become available from the sources cited in table 1. Figure 1 shows the helium mass fractions (Y) plotted against the logarithm of the ratio of the number of oxygen to hydrogen atoms in these galaxies; in some cases independent estimates of the same object are shown. We omitted several observations by Kinman & Davidson (1981) that we know to be of low weight, as well as the observations of IZw18 by French (1980), in which HeI λ4471 was not detected. We have included new observations by Davidson & Kinman (1982) of A2228 − 00 (HL 293B) and also the HII region no. 3 (which is excited by a Wolf Rayet star) (Sandage

Table 1. The primeval helium abundance (Y_p) derived from recent measurements of the helium abundance in dwarf galaxies

source of data	number of galaxies	Y_p α† = 0.006	Y_p α† = 0.003	$\sigma(Y_p)$‡
Lequeux *et al.* (1979) / Rayo *et al.* (1982)	10 / 1	0.232	0.236	±0.009
French (1980)	10	0.253	0.257	±0.026
Kennicutt *et al.* (1980)	1	0.228	0.231	—
Kinman & Davidson (1981) / Davidson & Kinman (1982)	7	0.246	0.248	±0.028
Tully *et al.* (1981)	1	0.236	0.238	—
Kunth (1981)	13	0.241	0.244	±0.011
higher weight observations§	26	0.236	0.240	±0.011

† The coefficient in the correction $\Delta Y = 10^4 \alpha\, n(\mathrm{O})/n(\mathrm{H})$.
‡ $\sigma(Y_p)$ is the r.m.s. deviation of a single value from the mean in the determination of Y_p.
§ Observations of Lequeux *et al.* (1979), Rayo *et al.* (1982), Kunth (1981) and Davidson & Kinman (1982). For details see text.

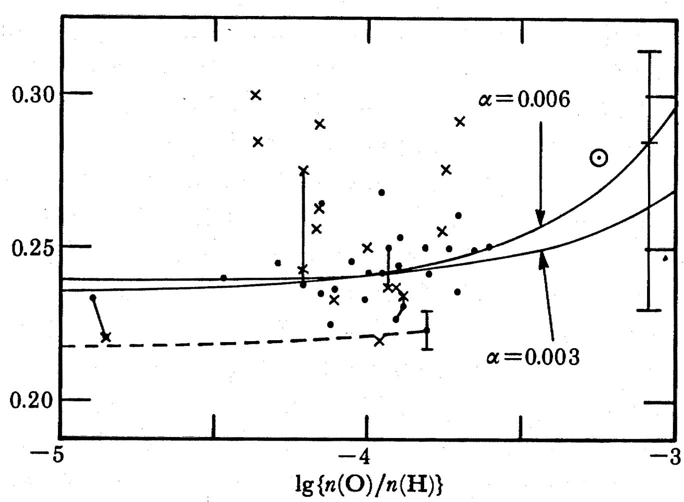

Figure 1. The mass fraction of helium (Y) plotted against the logarithm of the oxygen/hydrogen ratio by number for the dwarf galaxies listed in the references cited in table 1. Higher mass observations are shown by filled circles and the rest by crosses. Independent estimates for the same galaxy are joined by lines. Labelled curves show the run of the correction ΔY for two values of α as defined in table 1. The dashed curve shows the run of ΔY with $\alpha = 0.0038$ for NGC 5471, after Rayo *et al.* (1982). The large open circle gives the abundances for Orion (Rayo *et al.* 1982), and the observation with the large error bar at the extreme right is the estimate for the Sun by Heasley & Milkey (1978).

1971) in the Local Group galaxy IC 1613; these observations are based on long integrations and are of significantly higher weight than our earlier observations.

The curves in figure 1 represent two alternative helium–oxygen relations within the range proposed by various authors. Adopting one such curve, and shifting it up or down to make it pass through any particular point, one can estimate the Y_p corresponding to an observed Y. Clearly, the galaxies with low oxygen abundance (in the middle of the figure) have acceptably small post-primordial corrections, but the objects in our Galaxy (on the right side of the figure) do not.

The mean values of Y_p deduced for the galaxies observed by different authors are given in table 1. We judge the observations of Lequeux *et al.* (1979), Rayo *et al.* (1982), Kunth (1981) and Davidson & Kinman (1982) to be of higher quality, not only because their quoted errors are smaller but because they show a smaller scatter $\sigma(Y_p)$ in table 1. There are 26 galaxies in this group (filled circles in figure 1) and they give a mean Y_p of 0.236 or 0.240 depending on the assumptions made about ΔY. This is probably the best estimate of Y_p that we can make at the moment.

4. Future work

We suspect that observational error is largely responsible for the spread of the points in figure 1. If this is true, then $Y_p \approx 0.24$ – close to the value that we derived in §3. It is possible, however, that some of this scatter has other origins. In this case the value just mentioned is probably only a rough upper limit to Y_p – *assuming that Y_p is indeed uniform on a cosmological scale.* We note that one of the most outstanding points in figure 1 is for the well observed H II region NGC 5471 in M 101, for which the Y_p derived by Rayo *et al.* (1982) is 0.216 ± 0.010 (3σ). Possibly the observational errors are larger than we expect: in this case it is not clear at present how they can be reduced. If the helium abundance in NGC 5471 is really that low, then there may be problems that we do not understand in deriving Y_p. It is not at present clear whether it is more correct to calculate our primeval helium abundance from the single well-measured source that gives the lowest Y_p or to deduce it from a number of sources as we did in §3.

We have emphasized that it is important to derive Y_p from metal-poor galaxies. Unfortunately, the known objects of this kind are rather faint and, up to now, the advantage of a small ΔY correction has been offset by Y determinations of lower accuracy than have been available for brighter, more metal-rich, galaxies. To rectify this we have been re-observing some of the most metal-poor galaxies. In particular, IZw18 is very important because it is the most metal-poor galaxy known (at the extreme left of figure 1), but its abundances are not extremely well determined. We therefore observed that galaxy in February 1982, with the Kitt Peak 2.1 m telescope and image dissector scanner with a total integration time of 16 h – more than has previously been devoted to a single object. The data are not yet reduced, but some statistics are available that give an idea of the observational difficulties. The helium abundance will depend mostly on our estimate of the strength of the He I λ5876 line, which gave us about 10000 detector counts. These counts must be considered together with the 150000 counts from the object's continuum, the underlying night sky, and the night sky in the other channel. So at best, from a rough estimate based on the counting statistics alone, we have an uncertainty of about ± 400 counts or 4% of the line intensity. Spectrophotometry of this quality or better is needed for more very metal-poor galaxies if further progress is to be made; although data of this precision may be obtainable with less observing time with more efficient equipment, it is still not a trivial task.

It is clearly very important to try to find more emission-line galaxies such as IZw18 with very low metal abundances. A promising technique is to detect these objects by their emission lines from an objective-prism survey with a Schmidt telescope (see, for example, Kunth *et al.* 1981). One of us (T.D.K.) is currently making such a survey for Hα emission galaxies both in the general field and near large galaxies where dwarf companions are often found. Figure 2 shows the part (only about 1 % by area) of one of our 5° × 5° survey plates that includes the H II regions in the giant spiral M 101. There is known to be an abundance gradient in this galaxy in which the O/H ratio decreases outwards. NGC 5471 (discussed above) is in an outer spiral arm; we have been obtaining spectra of the even more remote companion NGC 5477 in the hope that its abundances may prove lower still. Unfortunately, the lines in NGC 5477 have only about half the strength of those in IZw18, and so the integration times needed are very long with our present equipment.

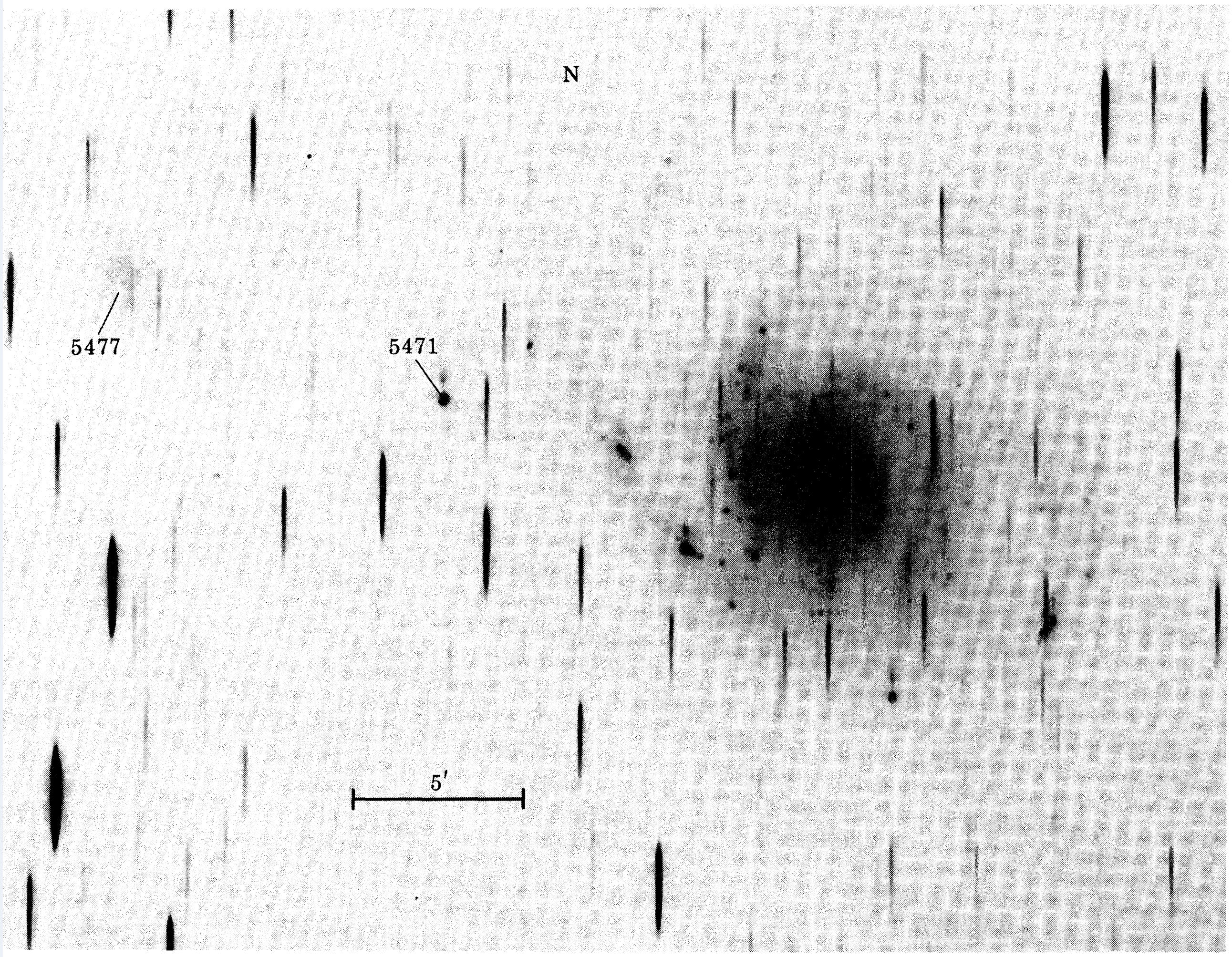

Figure 2. The field of M 101 showing the H II regions (including NGC 5471 and NGC 5477) from a 3 h exposure by C. T. Mahaffey with the 0.6 m Burrell Schmidt (IIIa-F emulsion and RG 2 filter). The 10° objective prism was used to give a dispersion on the plate of 400 Å mm^{-1} at Hα (1 Å = 10^{-10} m = 10^{-1} nm); the faintest detectable H II regions on this plate have an Hα flux of about 2×10^{-21} W cm^{-2}.

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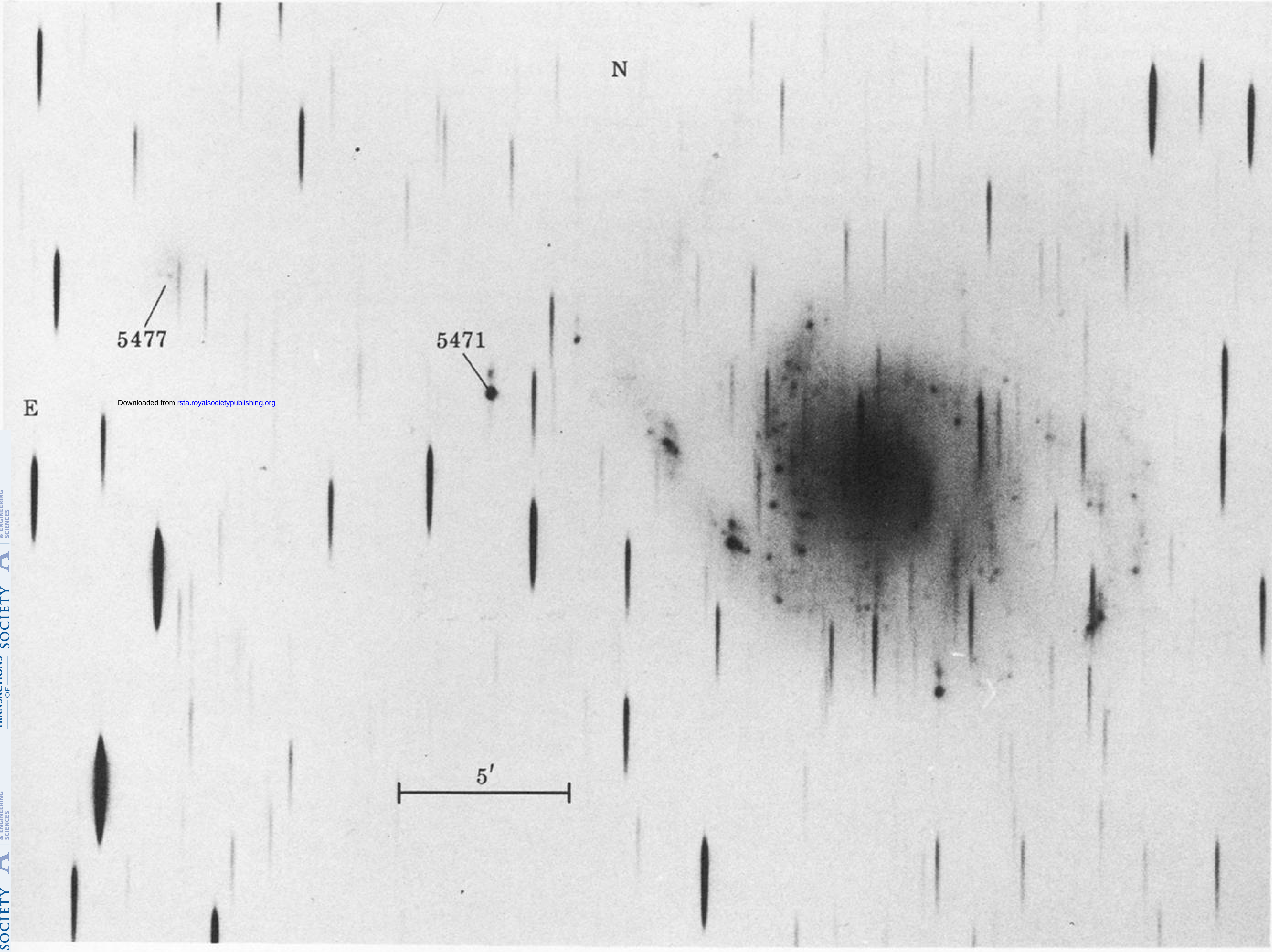

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