THE ASTROPHYSICAL JOURNAL, 164:L113–L118, 1971 March 15

ON THE DISTANCES OF THE QUASI-STELLAR OBJECTS

JAMES E. GUNN
Hale Observatories, California Institute of Technology,
Carnegie Institution of Washington
Received 1971 January 16

ABSTRACT

It is shown that Ton 256 ($z = 0.131$) and PKS 2251+11 ($z = 0.323$) are associated with galaxies of essentially the same redshift, thus implying that these objects are at cosmological distances. The nature of Ton 256 is questionable, and it is argued that it represents a transition between Seyfert galaxies and QSOs. There is no doubt that PKS 2251+11 is a bona fide QSO; it is bright ($M_v = -24.7$), blue ($B - V = 0.20$, $U - B = -0.84$), has a starlike image under high resolution, and is a strong radio source. A peculiar emission structure near PKS 2251+11 is also discussed.

The question of distances to the QSOs has been open since their nature was first discussed in the light of their large redshifts (Greenstein and Schmidt 1964). The hypothesis that they are "local," with distances of the order of tens of megaparsecs (Hoyle and Burbidge 1966; Hoyle and Fowler 1967; Terrell 1964; Arp 1966), has been supported mainly on the grounds that their variations are very difficult to explain if they are at the cosmological distances implied by their redshifts. The discovery of luminous, optically variable N-type galaxies and Seyfert nuclei which are certainly distant has somewhat weakened these theoretical arguments, and it is now widely—though certainly not universally—accepted that they are at cosmological distances, but as yet no conclusive positive evidence has been offered.

It has been shown (Bahcall, Schmidt, and Gunn 1969) that the object B264 is in a cluster of galaxies with the same redshift. The object, however, is significantly less luminous than bright galaxies, and Arp (1970) has shown it to be nonstellar; it is probably an N-type galaxy. The positive association of a cluster with a bona fide QSO would provide clear, direct confirmation of the cosmological nature of these objects. It is the purpose of this Letter to report two such cases of association: one, as before, somewhat clouded by the uncertain nature of the object (Ton 256), the other seemingly conclusive (PKS 2251+11).

That the cluster Zw 1612.7+2624 was superposed on Ton 256 was first noted by Bahcall and Bahcall (1970), who give estimated magnitudes for the members. The object Ton 256 was included in the original list of radio-quiet QSOs by Sandage (1964), but was recently found by Arp (1970) to be nonstellar, and, in fact, clearly to possess an envelope of some 15–20 kpc extent. Surface photometry is impossible because of the bright nucleus, but the photograph suggests that the nonthermal source is in the nucleus of a giant elliptical galaxy. The case for this object is quite different than for B264, however, since even if the contribution from Hβ and the nebular lines is omitted, the absolute rest-frame V-magnitude of the source is -22.7 if one takes $z = 0.131$, $V = 15.4$ (Iriarte 1959), $H = 75$, and 0.3 mag correction for the emission lines. Unpublished scans by J. B. Oke corroborate this value. The brightest galaxies have a mean visual absolute magnitude of -22.0 with a standard deviation of about 0.3 mag (Sandage 1968); thus the nucleus of Ton 256 is probably at least as bright as the brightest galaxies. If it is shown that the really bright QSOs are at cosmological distances, Ton 256 suggests itself as an excellent example of an intermediate case between the Seyfert nuclei and the QSOs. It should be noted that III Zw 2 is another such overluminous, presumably nonthermal, source with a companion with measured redshift (Sargent 1970).

All of this, of course, assumes that the redshift of Ton 256 itself is cosmological in origin, and since any stellar spectral features from the underlying galaxy are completely obliterated by the nonthermal radiation from the nucleus, this is not by any means obviously the case. Spectra at 190 Å mm^{-1} have been obtained with the 200-inch Cassegrain image-tube spectrograph for galaxies 1, 2, and 11 of Bahcall and Bahcall, and for a galaxy (B) 8″ south-preceding Ton 256, visible clearly on Arp's published photograph.

The results for objects 1, 2, and B are summarized in Table 1; the spectrogram of galaxy 11 was of very poor quality, and no redshift was obtained; it seems certain, however, that it is very different from 0.131. For all three of the others, the H- and K-lines and the G-band were easily measurable, and the agreement with the emission redshift of Ton 256 is excellent. Galaxy B, in particular, which is only 20 kpc distant in projection, agrees exactly to within the errors, about 300 km sec^{-1}. *If* the real distance is the projected distance, and *if* the motion is in the line of sight, this implies a maximum mass for Ton 256 of $10^{12}\,\mathfrak{M}_{\odot}$; there is, of course, no reason to assume the above conditions true, but it seems unlikely that the mass is enormously greater than ordinary galactic masses.

There seem to be no grounds for reservations about the nature of PKS 2251+11. A photograph of PKS 2251+11 obtained with an ITT 4708 image converter at the prime focus of the 200-inch telescope with a filter combination passing the 6000–7000 Å band is shown in Figure 1 (Plate L2). The image is starlike within the resolution, except for a jet-like protuberance to the south, the reality of which is doubtful. Arp (1970) has concluded on the basis of a 200-inch plate of comparable resolution that the object is starlike and that, if one insists on this quality for "real" QSOs, it is a bona fide QSO.

A scan obtained with the multichannel spectrometer (Oke 1969) on the 200-inch is presented in Figure 2 (a continuum scan has been published earlier by Oke and Neugebauer 1970, and the emission spectrum has been studied by Wampler 1968). If its redshift of 0.323 is cosmological, its continuum flux alone gives an absolute visual magnitude of -24.7 in its rest frame (for $q_0 = \frac{1}{2}$, $H = 75$), safely in the category of very powerful sources. The spectrum is quite flat, the continuum spectral index through the optical and near-ultraviolet being about -0.5. This index extrapolates the spectrum neatly to the 2000-MHz radio point, but the infrared (2 μ) point is a bit high. The corresponding colors are quite blue ($B - V = 0.20$, $U - B = -0.84$), in the middle of the range of "normal" QSO colors (Burbidge and Burbidge 1967).

It is evident from Figure 1 that PKS 2251+11 is superposed on a small, compact cluster of galaxies, largely contained in the small, field of the image-tube plate. Most of these galaxies are visible on Arp's plate of this object. The brightest of these is galaxy 1, 28″ distant from the QSO. A scan of this object is presented in Figure 3. The wavelength resolution is 80 Å between $\lambda\lambda$5400 and 6000, 160 Å to the red and blue of those points. The sharp drop characteristic of galaxies at $\lambda \sim 4000$ Å, due mainly to the H- and K-lines of Ca II, occurs clearly at about λ5320, a fit to the "standard" spectrum of Oke and Sandage (1968) yielding a redshift of 0.33 ± 0.01.

This "standard" elliptical galaxy, synthesized from the nuclei of M31 and NGC 3379,

TABLE 1

TONANTZINTLA 256 CLUSTER-GALAXY REDSHIFTS

Object	Ca II H	Ca II K	G-band	Mg I "*b*"	Average
B&B* No. 1....	0.118	0.127	0.110	0.126	0.1205±0.005
B&B No. 2.....	0.1308	0.1313	0.1313	0.134	0.1318±0.001
Ton 256B......	0.1313	0.1319	0.1320	...	0.1317±0.001

* Bahcall and Bahcall (1970).

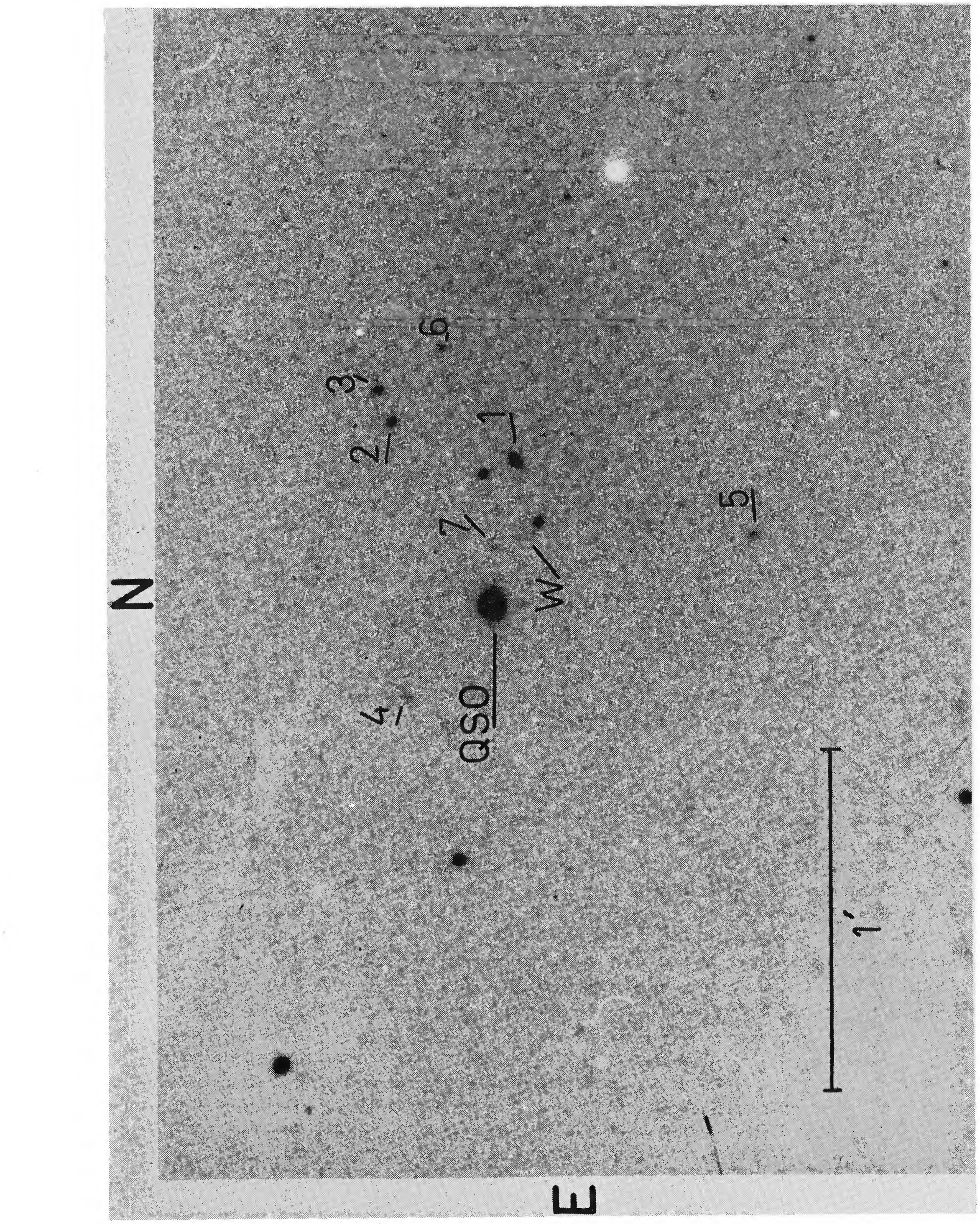

FIG. 1.—PKS 2251+11 and associated objects. The exposure was 20 minutes with an ITT 4708 image tube on baked IIIa-J emulsion behind a filter made up of 3 mm BG38 + 4 mm OG2. The photograph was obtained at the prime focus of the 200-inch telescope with the use of the Ross f/3.67 corrector.

GUNN (*see* page L114)

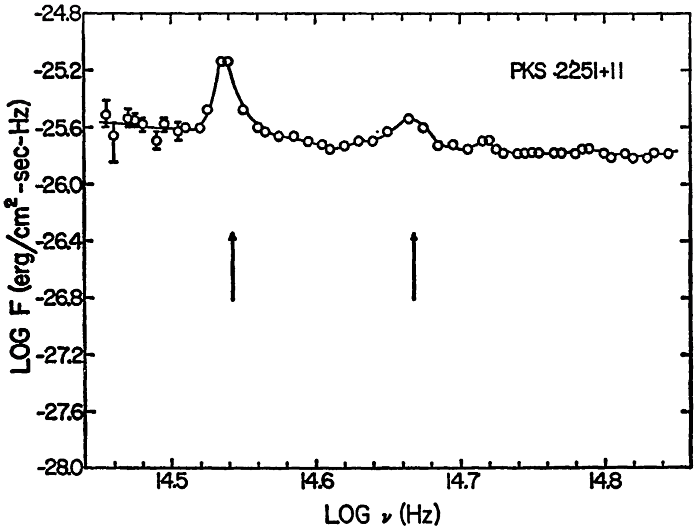

FIG. 2.—Multichannel scan of PKS 2251+11. *Arrows*, Hα and Hβ. Diaphragm size was 10″

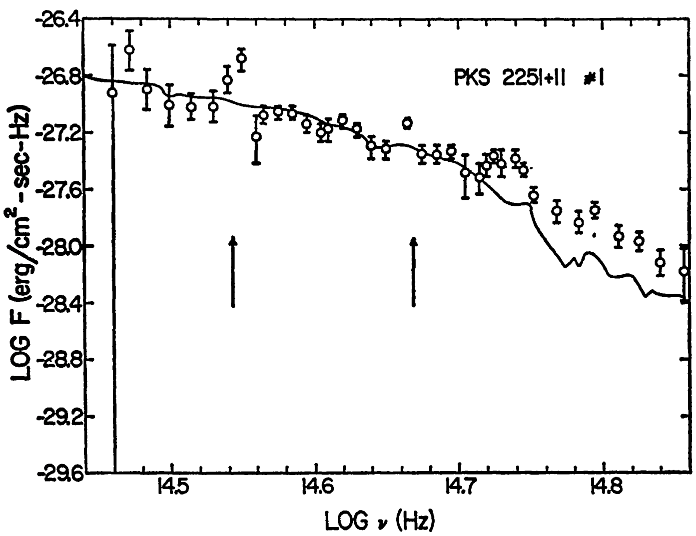

FIG. 3.—Multichannel scan of 2251+11 galaxy 1. *Light solid line*, a "standard" elliptical spectrum redshifted to $z = 0.323$. (See text.) Diaphragm size was 7″.

is shown by comparison, redshifted to $z = 0.323$. The drop at rest wavelength ~5200, due mainly to the Mg I *b*-lines, is also seen, as well as the structure to the blue of H and K. The only discrepancy seems to be the weakness of the G-band and the uniformly higher ultraviolet. It is clear from the photograph, however, that galaxy 1 is not an elliptical, but is highly elongated, with a pronounced centered nucleus. An Sb spiral with its younger stellar population would have exactly the required spectral properties, and it is concluded that the system is probably a middle-to-late spiral. The redshift is clinched by the appearance of Hα and Hβ in emission; the arrows indicate the predicted locations of the lines for $z = 0.323$.

We conclude finally that the redshift of galaxy 1 is the same as that of the QSO, to within an estimated total uncertainty of 3 percent, 0.01 in z, or about 3000 km sec^{-1}.

The appearance of the Balmer lines in emission at the observed level is puzzling. The nucleus of the galaxy is bright but extended, and it seems unlikely that it is a Seyfert. The Hβ flux is 5×10^{-15} ergs cm^{-2} sec^{-1}, corresponding to a luminosity of 1×10^{42} ergs sec^{-1} in the frame of the galaxy. Taking the Hβ emissivity to be (Aller and Liller 1968)

$$j_\beta \simeq 10^{-25} N_e^2 (10^4/T) \text{ ergs sec}^{-1}$$

and taking the gas in the galaxy to be in a disk 10 kpc in radius and 200 pc thick (the radius corresponding to the measured image, the thickness a blind guess that our Galaxy is representative), we find that the desired value of $\langle N_e^2 \rangle$ is about 5 for temperatures around 10^4 ° K. Thus, *most* of the hydrogen must be ionized if the galaxy is typical of our own. What provides the flux of ionizing radiation? The obvious candidate is the QSO. For the observed Hβ flux, the number of recombinations leading to the emission of Balmer photons is of order 10^{54} sec^{-1}. The extrapolated luminosity for the QSO is 1.6×10^{30} ergs sec^{-1} Hz^{-1} at the Lyman limit, corresponding to about 5×10^{53} ionizing photons per second incident on the galaxy if its distance from the QSO is about equal to its projected distance of 100 kpc.

The galaxy is easily calculated to be very thick in the Lyman lines, so Menzel and Baker's case B applies, for which one Balmer photon is created per recombination, and within a very uncertain factor of 2 the ionizations expected from the present QSO flux balance the observed recombinations. The primary uncertainties are the solid angle, projection effects, and the obvious fact that the flux seen by the galaxy refers to an epoch perhaps 3×10^5 years earlier than the measured QSO flux. The weakness of the forbidden lines, particularly λ3727 and the nebular lines, might be explained either by low temperatures or very high ionization resulting from the flat ultraviolet spectrum of the QSO. This problem will be pursued in a later paper.

The absolute proper visual magnitude of the galaxy for $H = 75$, $q_0 = \frac{1}{2}$ is -21.2 from the scan; the apparent visual magnitude is about 20.3. The other galaxies in the group are fainter yet, probably prohibitively faint for either spectra or scans; the scan of galaxy 1 required nearly 4 hours of telescope time, and comparable accuracy on even galaxy 2 would require a whole night. Thus, while a check on other members of the group would be desirable, it seems an impossible task with present instrumentation.

One can, however, ask the following question: What is the probability of finding a galaxy of absolute magnitude -21 or brighter within 30″ of a given random position and within 3000 km sec^{-1} of a given redshift near 0.3? The answer is a realistic assessment of the probability of a chance coincidence, if possible physical connections such as the ionization in the galaxy are ignored. The calculation of this probability would be trivial if the luminosity function for galaxies were well known, since the absolute magnitude and the volume (about 1.3 Mpc^3 transformed to the present epoch) is known. There is evidence that the luminosity function in clusters differs from that in the field, and neither is well determined. If we use Kiang's (1961) luminosity function for field galaxies as probably the best compromise, the a priori probability is about 1.0×10^{-3}. This should, of course, be multiplied by the number of trials, and this is difficult to assess realistically. Image-tube plates of comparable quality have been obtained for six objects, these being selected on the basis of right ascension and redshift ($z \leq 0.35$) alone. Of these, four (PKS 2251+11, PHL 1093, Ton 256, PKS 2135−14) have "suspicious" associated galaxies. For the objects reported on here, the galaxies have concordant redshifts. Of the others, only PKS 2135−14 has been investigated spectroscopically, but no plates of sufficiently good quality to measure redshifts were obtained. The reader may come to his own conclusions; the author feels that a realistic estimate of the probability is no larger than about 2×10^{-3}.

There is one further piece of supporting evidence. The nebulous object labeled W (Wisp) on the plate was scanned. The result (Fig. 4) has a rather poor signal-to-noise

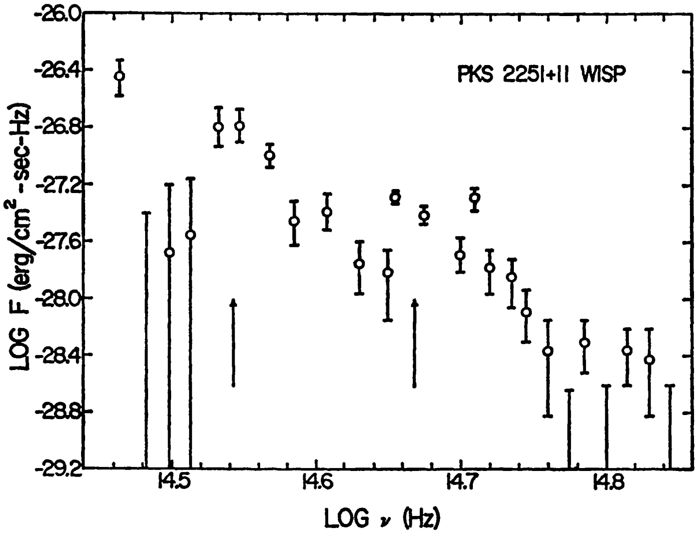

FIG. 4.—Multichannel scan of 2251+11 Wisp. *Arrows, redshifted* locations of Hα and Hβ. Diaphragm size was 7″.

ratio, and no comments on the fascinating possibilities of the object's nature and origin will be made here, except to note that it seems to be, or to be connected with, an extended H II region, presumably also excited by the QSO, and showing peaks at the redshifted wavelengths of Hα, Hβ, and possibly Hγ. The probable errors are large, and by itself the data would not be convincing, but they add some weight to the case. If better data corroborate the general features of Figure 4, gravitational-redshift models can be ruled out even without the results on galaxy 1.

We conclude that the object PKS 2251+11 satisfies the most stringent requirements for inclusion in the class of quasi-stellar objects and that it is almost certainly at the same distance as a galaxy of essentially the same redshift. The case for such objects as Ton 256 and III Zw 2 being intermediate between QSOs and Seyfert nuclei is strengthened. It should be noted, finally, that a galaxy even somewhat brighter than galaxy 1 could quite easily be superposed on PKS 2251+11 and be completely undetectable. The clear association of QSO-like activity with galactic nuclei at all luminosity levels up to and including the luminosity of the brightest galaxies, together with the evidence that at least one "real" QSO has a cosmological redshift, makes the picture of QSOs as events *in* galaxies compelling, and indeed at this point the most conservative of the various possibilities offered to date.

The author would like to thank Professors Maarten Schmidt and John Bahcall for useful discussions on this problem, and Gary Tuton for expert observing assistance. Thanks go especially to Professor J. B. Oke for instruction on the use of the spectrometer, for assistance and discussions on the tedious task of data reduction, and interesting discussions about the problem itself.

REFERENCES

Aller, L. H., and Liller, W. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press).
Arp, H. C. 1966, *Science*, **151**, 1214.
———. 1970, *Ap. J.*, **162**, 811.
Bahcall, J. N., and Bahcall, N. 1970, *Pub. A.S.P.*, **82**, 721.
Bahcall, J. N., Schmidt, M., and Gunn, J. 1969, *Ap. J.* (*Letters*), **157**, L77.

Burbidge, E., and Burbidge, G. 1967, *Quasi-stellar Objects* (San Francisco: W. H. Freeman & Co.).
Greenstein, J. L., and Schmidt, M. 1964, *Ap. J.*, **140**, 1.
Hoyle, F., and Burbidge, G. R. 1966, *Ap. J.*, **144**, 534.
Hoyle, F., and Fowler, W. 1967, *Nature*, **213**, 373.
Iriarte, B. 1959, *Lowell Obs. Bull.*, **4**, 130.
Kiang, T. 1961, *M.N.R.A.S.*, **122**, 263.
Oke, J. B. 1969, *Pub. A.S.P.*, **81**, 11.
Oke, J. B., and Neugebauer, G. 1970, *Ap. J.*, **159**, 341.
Oke, J. B., and Sandage, A. R. 1968, *Ap. J.*, **154**, 21.
Sandage, A. R. 1964, *Ap. J.*, **141**, 1560.
———. 1968, *Ap. J.* (*Letters*), **152**, L149.
Sargent, W. L. W. 1970, *Ap. J.*, **160**, 405.
Terrell, J. 1964, *Science*, **145**, 918.
Wampler, E. J. 1968, *Ap. J.*, **153**, 19.