1.3 THE ELECTROMAGNETIC SPECTRUM OF THE CRAB NEBULA

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Abstract. I shall discuss observations of the spectrum of the integrated emission from the Crab Nebula. The radio data with accurate calibrations lead to a flux density spectral index of -0.26. Discrepancies in the published fluxes at millimetre wavelengths can be resolved if appropriate angular dimensions are used. In the optical range the spectral index has increased to a value of -0.9 if $1^{\mathrm{m}}.0$ of absorption is used. At X-ray wavelengths the spectral index has increased further to -1.2.

1. Introduction

The spectrum of the integrated radiation from the Crab Nebula might be thought to be of very little importance. Evidently there are contributions from a wide variety of sources – the filaments, the amorphous nebula, the wisps, the compact low frequency source and the pulsar. The spectra of these components are likely to be, and in some cases known to be, very different from each other. But observers continue to attempt to measure the overall spectrum with greater accuracy and I believe this work to be important for two reasons

(1) The integrated radiation is the only quantity which can be measured with any ease.

(2) The combination of an integrated spectrum with detailed mapping at a number of fixed frequencies gives us the spectra of all points over the face of the nebula.

The separation of the two technical problems of absolute determinations of intensity and high resolution mapping of relative intensities seems at present to give us the best hope of obtaining the details of the spectrum as a function of position in the nebula – the primary data needed for any physical model.

I shall present data over the whole observed frequency range but I shall leave detailed discussion of the X- and γ-ray observations to those more competent to discuss them. There are still gaps in the observed spectrum and it is convenient to discuss the observations in separate groups.

2. The Radio Spectrum $10^7 < \nu < 2.5 \times 10^{11}$ Hz

In the radio range there is, relatively speaking, a very large power flux available. If radioastronomers ever thought of photons, they would find photon counting rates in their experiments which are typically $> 10^{10}$ sec^{-1}. They therefore use voltages and currents and I shall refer to flux densities in terms of $\mathrm{Wm}^{-2}\,\mathrm{Hz}^{-1}$ and apply this in all parts of the spectrum.

The technical problems in the radio region are those of accurate calibration of equipment, especially over wide ranges of frequency. Measurements are usually made

Davies and Smith (eds.), The Crab Nebula, 22–31. *All Rights Reserved.*

in narrow frequency bands. The so-called absolute determinations rely on experimental or theoretical values of the scale of antenna temperature and the antenna gain. Relative determinations rest on comparisons with other sources such as planets, the Moon or an artificial Moon whose flux density is believed to be known. I include all observations in which absolute calibrations were made and most of those using relative calibrations where they have seemed to me to be in some sense independent. The difficulty here is that the various scales of flux density now in use are in some cases dependent on an assumption about the smoothness of the radio spectra of the sources which form the basis of the scale. The Crab Nebula is often one such basic source.

I take this opportunity to mention that many of the values obtained are not satisfactorily described by the authors. Some merely note that the Moon was used as a calibrating source without saying in what way. Values quoted by other authors change in successive papers without it being clear whether the later values supersede the former due to advances in technique or recalculation or whether they are just independent estimates.

In Table I and Figure 1 are assembled the radio flux densities I have found in the literature, nearly all of them post 1960. In Figure 1 I have omitted a few values whose error limits are too large to be useful now. It is probable that, to the accuracy of the present discussion, we can ignore any secular variations in the flux densities. It is clear that the range 0.1–10 GHz is the best for accurate measurements. At low frequencies it is difficult to detect the source with simple antennas of calculable gain and in any case ionospheric scintillation makes observations difficult. At high frequencies it is difficult to construct accurate antennas of large collecting area, there are no very good standards of noise power and atmospheric attenuation is very important.

The most serious discrepancies between observers are at mm wavelengths ($\nu > 3 \times 10^{10}$ Hz). One possible explanation would be in the use of Jupiter as a reference source. The disc temperature is frequently assumed to be 150 K. This may well be incorrect and perhaps by large amounts if there are absorption lines in the Jovian

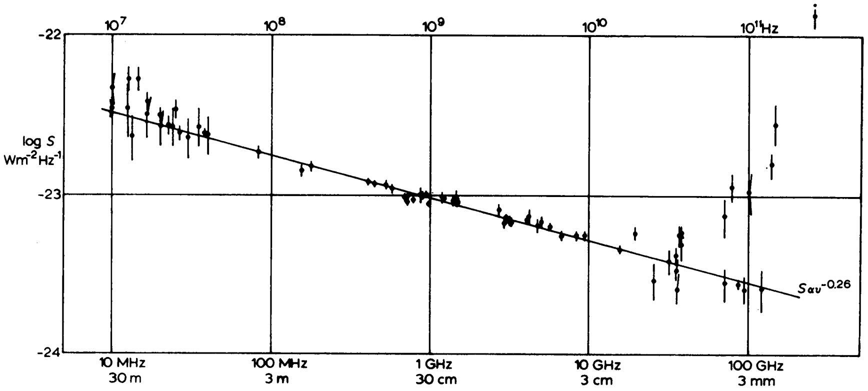

Fig. 1. Radio spectrum of total radiation from the Crab nebula.

TABLE I

Measurements of the flux density of the integrated emission from the Crab Nebula

Author	Frequency	Flux density 10^{-26} W m^{-2} Hz^{-1}	Error %
Clark (1966)	10 MHz	3500	10
Bridle and Purton (1968)	10	4650	25
Baselyan *et al.* (1963)	12.5	3500	40
Braude *et al.* (1969)	12.6	5300	15
Andrew (1967)	13.1	2350	30
Braude *et al.* (1969)	14.7	5300	15
Braude *et al.* (1969)	16.7	3830	14
Baselyan *et al.* (1963)	16.7	3200	40
Baselyan *et al.* (1963)	20	2700	30
Braude *et al.* (1969)	20	3170	14
Roger *et al.* (1969)	22.25	2750	12
Baselyan *et al.* (1963)	24	2700	30
Braude *et al.* (1969)	25	3420	14
Erickson and Cronyn (1965)	26.3	2440	11
Baselyan *et al.* (1963)	30	2300	30
Baselyan *et al.* (1963)	35	2700	30
Williams *et al.* (1965)	38	2430	5
Baselyan *et al.* (1963)	40	2400	30
Parker (1968)	81.5	1880	10
Parker (1968)	152	1430	10
Kellermann *et al.* (1969)	178	1534	5
Baars *et al.* (1965)	400	1229	3.8
Baars *et al.* (1965)	440	1192	3.7
Alekseev *et al.* (1969)	518	1180	3
Lastochkin *et al.* (1963)	562	1110	6
Alekseev *et al.* (1969)	680	980	4.5
Lastochkin *et al.* (1963)	708	910	5
Alekseev *et al.* (1969)	714	980	4.5
Alekseev *et al.* (1969)	770	940	3
Lastochkin *et al.* (1963)	860	1016	10
Alekseev *et al.* (1969)	870	1030	3
Lastochkin *et al.* (1963)	876	1000	3
Razin and Fedorov (1963)	927	1025	4
Alekseev *et al.* (1969)	986	890	3
Lastochkin *et al.* (1963)	1.19 GHz	980	7
Baars *et al.* (1965)	1.20	971	3
Kellermann *et al.* (1969)	1.40	930	5
Mezger (1958)	1.419	968	12
Baars *et al.* (1965)	1.44	913	3
Altenhoff *et al.* (1961)	2.70	811	10
Sloanaker and Nichols (1960)	2.93	670	10

Tabel I (continued)

Author	Frequency	Flux density 10^{-26} W m^{-2} Hz^{-1}	Error %
Baars *et al.* (1965)	3.00 GHz	733	3.5
Medd and Ramana (1965b)	3.15	695	5
Broten and Medd (1960)	3.20	680	5
Wilson and Penzias (1966)	4.08	711	3
Yokoi (1966)	4.17	745	10
Golnev *et al.* (1965)	4.69	650	
Kellermann *et al.* (1969)	5.00	680	5
Dmitrenko and Strezhneva (1967)	5.68	646	5
Medd and Ramana (1965a)	6.66	565	5
Allen and Barrett (1966, 1967)	8.25	567	4.8
Lazarewski *et al.* (1963)	9.36	560	5.4
Allen and Barrett (1966)	15.5	461	5.9
Williams *et al.* (1965)	19.6	588	9
Staelin *et al.* (1964)	25.4	295	28
Hobbs *et al.* (1968)	32	387	18
Kalaghan and Wulfsburg (1967)	34.9	340	+19 −12
Tolbert and Straiton (1965)	35	420	14
Lynn *et al.* (1964)	35.3	260	25
Tolbert and Straiton (1965)	36.2	420	15
Matveenko and Pavlov (1967)	36.6	565	14
Kuzmin and Salomonovich (1962)	37.5	500	25
Barrett *et al.* (1965)	37.5	600	8
Hobbs *et al.* (1969)	69.75	281	26
Tolbert (1965)	70	750	28
Kisljakov and Lebsky (1967)	77.5	1130	21
Matveenko (1970)	85.6	280	7
Oliver *et al.* (1967)	93	260	19
Tolbert (1965)	100	1080	30
Efanov *et al.* (1969)	139	1600	13
Kisljakov and Naumov (1967)	142	2800	32
Zabolotny *et al.* (1970)	120	250	30
Beckman *et al.* (1969)	250	13400	15

atmosphere. A more likely explanation, as noted by Hobbs *et al.* (1969), lies in the corrections to the observed flux densities due to the finite angular size of the Crab Nebula when narrow beamwidths are used. In some cases the corrections applied have been certainly too large. If one takes the size as measured, for example, at 6 cm by Wilson (see paper 1.8, page 68, in this symposium) which can be represented approximately by Gaussians with half-widths of 2.2′ and 3.4′ respectively, then the short wavelength measurements when corrected are as shown in Figure 2. There is

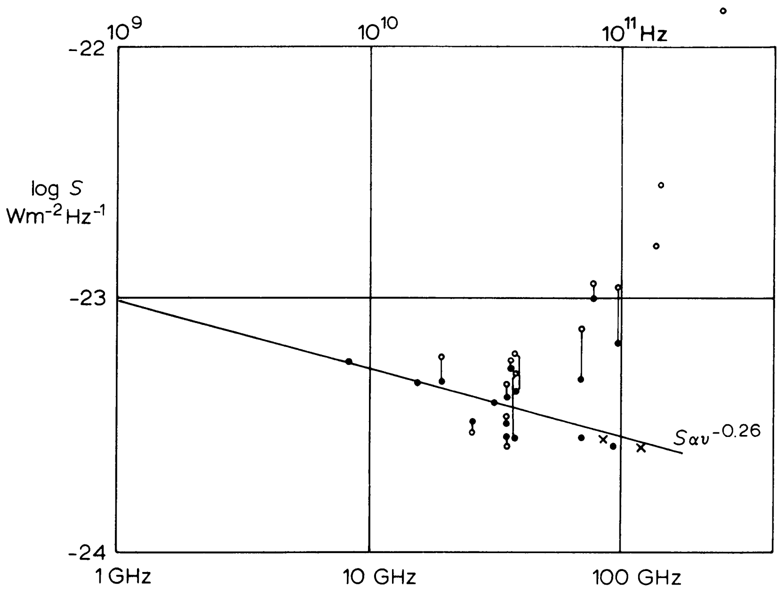

Fig. 2. High frequency radio spectrum. ○ Published values. ● Values corrected for a standard source size.

now much less evidence for an increase in flux density towards the high frequencies. Of the three very discrepant points, that of Efanov *et al.* (1969) at 139 GHz (2.16 mm) was made with a telescope operating at a much shorter wavelength than that for which it was designed and that of Kisljakov and Naumov (1967) at 142 GHz (2.11 mm) was made with a small telescope giving a very small signal to noise ratio. Only the measurement of Beckman *et al.* (1969) is unaccounted for. I take the now old fashioned view that exciting results require further experimental confirmation.

The two points marked by × in Figure 2 are those of Matveenko and Zabolotny which were announced at the IAU General Assembly subsequent to Symposium 46. The present evidence seems to strongly favour a straight line spectrum over the whole radio region having a spectral index α, defined by flux density $\propto$ (frequency)$^\alpha$, of -0.26.

3. The Infrared and Optical Spectrum

The evidence available has recently been reviewed by Scargle (1969, 1970). In the optical range there is little disagreement between observers and the best line through the points is straight with a spectral index α of -2.5. In the infrared the early values by Moroz (1964) are probably superseded by those of Ney and Stein (1968) and Becklin and Kleinmann (1968) slightly corrected for source size. The main uncertainty lies in the correction for visual obscuration. Estimates of A_v of $1^{\mathrm{m}}\!.7$ have been most popular. In Figure 3 are presented both the observations and curves corrected for different values of the visual obscurations using the corrections as a function of

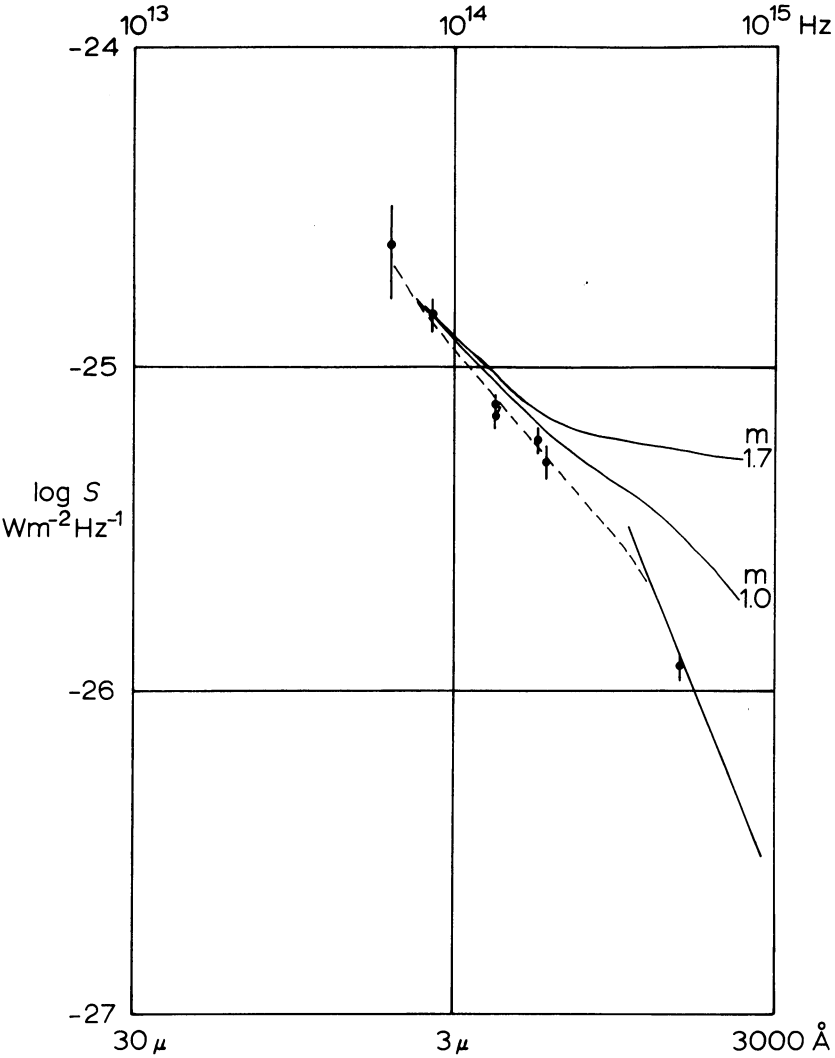

Fig. 3. Infra red and optical continuum spectrum of the Crab nebula. The several curves correspond to different magnitudes of visual obscuration.

frequency given by Becklin and Neugebauer (1968). Note that $1^{m}.0$ corresponds to a fairly smooth unabsorbed spectrum with spectral index −0.9. There may be good reason to suppose that this is near the correct value since, line emission excepted, it is extremely difficult to account for sharp features in the synchrotron spectrum of the nebula.

4. The X-Ray and γ-Ray Spectrum

At X-ray wavelengths there is again a large amount of experimental evidence. Most of the observers quote results in the form of a photon flux at a particular energy together with a value for the spectral index. A recent review by Peterson and Jacobson (1970) assembles most of the available data and no details will be given here. The spectra are plotted in Figure 4 without error limits. The scatter of observations is somewhat outside the quoted error limits but it is clear that over the range

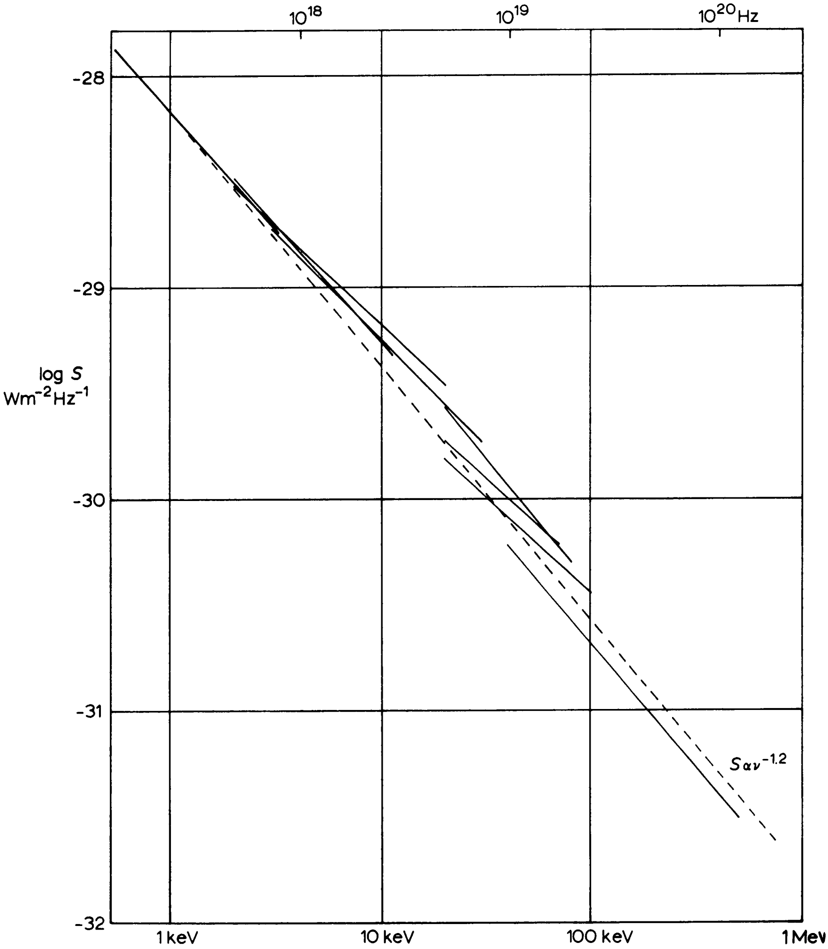

Fig. 4. X-ray spectrum of the Crab nebula. The mean spectra from different authors are plotted without error bars.

$2 \times 10^{17} < \nu < 10^{20}$ Hz the observations can be represented by a spectrum with spectral index α of -1.2. At frequencies $> 10^{20}$ Hz there are, as yet, only upper limits to the flux density.

The separate parts of the spectrum are presented together in Figure 5. The widths of the lines cover the limits of uncertainty in different parts of the spectrum. I conclude from this figure that a simple smooth spectrum can be drawn through the observations over the whole observed range having a spectral index of -0.26 for $10^7 < \nu < 10^{11}$ Hz, -0.9 for $6 \times 10^{13} < \nu < 10^{15}$ Hz and -1.2 for $2 \times 10^{17} < \nu < 10^{20}$ Hz. It seems more important to attempt new observations in the gaps in the spectrum than to improve the accuracy in those parts already studied.

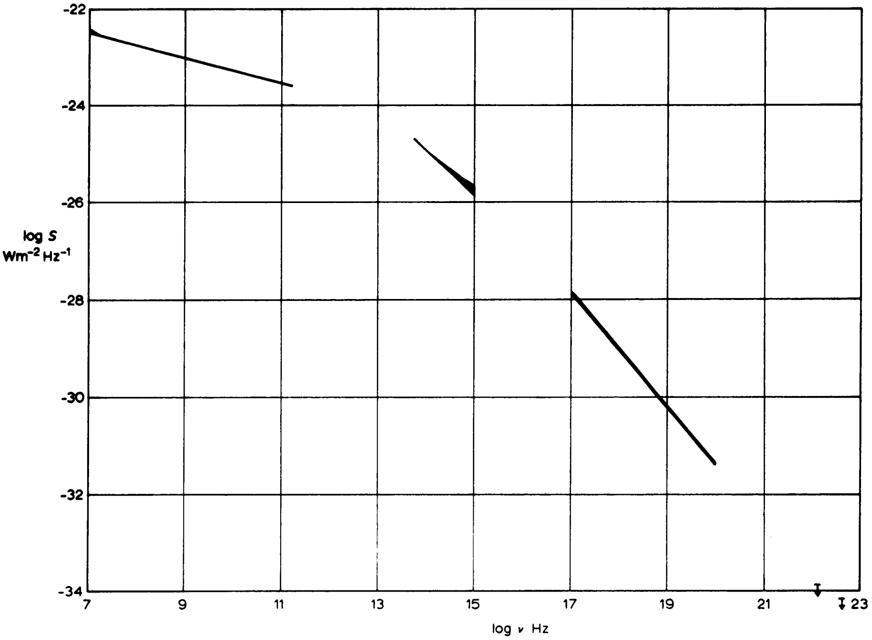

Fig. 5. The electromagnetic spectrum of the total radiation from the Crab nebula. The thickness of the lines covers the limits of uncertainty at any frequency. The upper limits at high frequencies are those of Frye and Wang (1969).

References

Alekseev, V. A., Gatelyuk, E. D., Dmitrenko, A. A., Romonychev, A. A., and Tseitlin, N. M.: 1969, *Radiofiz.* **12**, 168.

Allen, R. J. and Barrett, A. H.: 1966, *Astron. J.* **71**, 843.

Allen, R. J. and Barrett, A. H.: 1967, *Astron. J.* **72**, 288.

Altenhoff, W., Mezger, P. G., and Wendker, H.: 1961, *Veröff. Inst. Univ. Bonn* No. 59, Pt. IV.

Andrew, B. H.: 1967, *Astrophys. J.* **147**, 423.

Baars, J. W. M., Mezger, P. G., and Wendker, H.: 1965, *Astrophys. J.* **142**, 122.

Barrett, A. H., Kutuza, B. G., Matveenko, L. I., and Salomonovich, A. E.: 1965, *Soviet Astron.* **9**, 418.

Baselyan, L. L., Braude, S. Y., Krymkin, V. V., Men, A. V., and Sodin, L. G.: 1963, *Radiofiz.* **6**, 897.

Becklin, E. E. and Kleinmann, D. E.: 1968, *Astrophys. J.* **152**, L25.

Becklin, E. E. and Neugebauer, G.: 1968, *Astrophys. J.* **151**, 145.

Beckman, J. E., Bastin, J. A., and Clegg, P. E.: 1969, *Nature* **221**, 944.

Braude, S. Y., Lebedeva, O. M., Men, A. V., Ryabov, B. P., and Zhouck, I. N.: 1969, *Monthly Notices Roy. Astron. Soc.* **143**, 289.

Bridle, A. H. and Purton, C. R.: 1968, *Astron. J.* **73**, 717.

Broten, N. W. and Medd, W. J.: 1960, *Astrophys. J.* **132**, 279.

Clark, T. A.: 1966, *Astron. J.* **71**, 158.

Dmitrenko, D. A. and Strezhneva, K. M.: 1967, *Radiofiz.* **10**, 165.
Efanov, V. A., Kisljakov, A. G., Kostenko, V. I., Matveenko, L. I., Moiseev, I. G., and Naumov, A. I.: 1969, *Radiofiz.* **12**, 803.
Erickson, W. C. and Cronyn, W. M.: 1965, *Astrophys. J.* **142**, 1156.
Frye, G. M. and Wang, C. P.: 1969, *Astrophys. J.* **158**, 925.
Golnev, V. Y., Lipovka, N. M., and Parijsky, Y. N.: 1965, *Soviet Astron.* **9**, 690.
Hobbs, R. W., Corbett, H. H., and Santini, N. J.: 1968, *Astrophys. J.* **152**, 43.
Hobbs, R. W., Corbett, H. H., and Santini, N. J.: 1969, *Astrophys. J.* **155**, L87.
Kalaghan, P. M. and Wulfsburg, K. N.: 1967, *Astron. J.* **72**, 1051.
Kellermann, K. I., Pauliny-Toth, I. I. K., and Williams, P. J. S.: 1969, *Astrophys. J.* **157**, 1.
Kisljakov, A. G. and Lebsky, Y. V.: 1967, *Soviet Astron.* **11**, 561.
Kisljakov, A. G. and Naumov, A. I.: 1967, *Soviet Astron.* **11**, 1059.
Kuzmin, A. D. and Salomonovich, A. E.: 1962, *Soviet Phys. Dokl.* **6**, 745.
Lastochkin, V. P., Porfiriev, V. A., Stankevitch, K. S., Troitsky, C. S., Kholodilov, N. N., and Tseitlin, N. M.: 1963, *Radiofiz.* **6**, 629.
Lazarewski, V. S., Stankevitch, K. S., and Troitsky, V. S.: 1963, *Soviet Astron.* **7**, 8, 1963.
Lynn, V. L., Meeks, M. L. and Sohigian, M. D.: 1964, *Astron.* J. **69**, 65.
Matveenko, L. I. and Pavlov, A. V.: 1967, *Soviet Astron.* **11**, 300, 1967.
Matveenko, L. I.: 1970, preprint presented at IAU General Assembly, Brighton.
Medd, W. J. and Ramana, K. V. V.: 1965a, *Astron. J.* **70**, 327.
Medd, W. J. and Ramana, K. V. V.: 1965b, *Astrophys. J.* **142**, 383.
Mezger, P. G.: 1958, *Z. Astrophys.* **46**, 234.
Moroz, V. I.: 1964, *Soviet Astron.* **7**, 755.
Ney, E. P. and Stein, W. A.: 1968, *Astrophys. J.* **152**, L21.
Oliver, J. P., Epstein, E. E., Schorn, R. A., and Sotet, S. L.: 1967, *Astron. J.* **72**, 314.
Parker, E. A.: 1968, *Monthly Notices Roy. Astron. Soc.* **138**, 407.
Peterson, L. E. and Jacobson, A. S.: 1970, *Publ. Astron. Soc. Pacific.* **82**, 412.
Razin, V. A. and Fedorov, V. T.: 1963, *Radiofiz.* **6**, 1052.
Roger, R. S., Costain, C. H., and Lacey, J. D.: 1969, *Astron. J.* **74**, 366.
Scargle, J. D.: 1969, *Astrophys. J.* **156**, 401.
Scargle, J. D.: 1970, *Publ. Astron. Soc. Pacific* **82**, 388.
Sloanaker, R. M. and Nichols, J. H.: 1960, *Astron. J.* **65**, 109.
Staelin, D. H., Barrett, A. H. and Kusse, B. R.: 1964, *Astron. J.* **69**, 69.
Tolbert, C. W.: 1965, *Nature* **206**, 1304.
Tolbert, C. W. and Straiton, A. W.: 1965, *Astron. J.* **70**, 177.
Williams, D. R. W., Welch, W. J., and Thornton, D. D.: 1965, *Publ. Astron. Soc. Pacific* **77**, 178.
Wilson, R. W. and Penzias, A. A.: 1966, *Astrophys. J.* **146**, 286.
Yokoi, H.: 1966, *Publ. Astron. Soc. Japan* **18**, 271.
Zabolotny, V. F., Sholomitsky, G. B., and Slysh, V. I.: 1970, preprint presented at the IAU General Assembly, Brighton.

Discussion

V. Trimble: It now seems probable that the upper limit to the UV flux derived from the ratio of (O II) to (O III) is not in conflict with a smooth curve drawn from optical to X-ray observations. The rather low degree of ionization can be explained by a high helium abundance in the filaments (ionization of the helium 'soaking up' photons that would otherwise ionize O^+ to O^{++} further into the filaments).

R. C. Jennison: Dr. Baldwin offered some criticism of the high flux readings in the millimetre spectrum but did not discuss the reliability of the two readings just below the extrapolated mean flux line. The implication is that these readings are less subject to error and carry greater weight than all those above the line. Is this so or was Dr. Baldwin's argument conditioned by the beauty of the simple smooth spectrum?

J. E. Baldwin: There is little argument about the best curve at ~ 1 cm. At 8 mm I have shown that many of the observed points must be moved downwards towards the extrapolated spectrum from lower frequencies. The real argument concerns the points at yet shorter wavelengths. The values at 3.2 and 4.3 mm were both obtained with large telescopes designed for these short wavelengths and seem to be good values; that at 4.3 mm being particularly well documented by the authors.

M. M. Komesaroff: Is the optical flux density spectral index -0.25?

J. E. Baldwin: If we assume about $1^{\mathrm{m}}.0$ of absorption, giving an essentially straight spectrum at optical wavelengths, then the index is -0.9.

W. J. Cocke: Most of the very low frequency radio spectrum comes from the compact radio source, presumably from an entirely different emission process. The synchrotron continuum emission flux density would then have to decrease sharply at low frequencies.

J. E. Baldwin: I agree that the compact source is very important at low frequencies. However, both its contribution to the total radiation and the optical depth of interstellar H II in the line of sight to the Crab nebula are very uncertain and it is therefore extremely difficult to make a good assessment of the spectrum of the nebula itself at low frequencies.

F. C. Michel: It would be very difficult for a synchrotron source to drop in flux rapidly with decreasing frequency, since the low frequency drop off goes as $\nu^{+0.33}$ regardless of the energy spectrum of the electrons with $\nu_{\max} > \nu$. In other words the source can decrease arbitrarily rapidly with increasing frequency, but can increase no more rapidly than $\nu^{+0.33}$, provided of course that self-absorption is unimportant. Thus the rapid rise beyond 1 cm would be difficult to reconcile with the synchrotron model.

R. Minkowski: Why should one expect a perfectly smooth spectrum? The size of the nebula depends on the frequency. Wherever the size decreases, the integrated flux must decrease. This decrease is superimposed on all changes of spectral index. I see no reason why the result should be a perfectly smooth spectrum. If, as seems probable, the visual interstellar absorption is between 1.5 and 2.0 magnitudes a perfectly smooth transition from the optical to the X-ray region may be impossible.

J. E. Baldwin: The size of the nebula depends on frequency, that is to say that the spectrum of the radiation varies from point to point in the nebula. The spectra of individual regions may contain sharp features but, unless these features are the same for all regions, the integrated spectrum of the whole nebula will be much smoother. If the visual obscuration is really 2.0 magnitudes and there is an interruption of the smooth spectrum it may be very difficult to explain.

J. E. Felten: The shape of the spectrum integrated over the entire nebula gives the first indication of how complicated one's theoretical model must be. Thus (to take a simple case) if the continuum emission from a source is entirely synchrotron radiation from electrons injected continuously in a power law at one point or several points in a uniform field, then the integrated spectrum, say in the optical and ultraviolet, may be a simple power law (resulting from equilibrium between injection and energy loss), even though the spectrum revealed by a smaller diaphragm is a function of position and presents more complications. Therefore it is good to look first for simplicity in the integrated spectrum, as Dr. Baldwin has done.

W. J. Cocke: But then you must take out the compact source component.