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SPECTRA OF CASSIOPEIA A. I. OBSERVATIONS

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ABSTRACT

Image-tube spectrograms of the supernova remnant Cas A in the wavelength range 4700–8000 Å have been reduced to give relative line intensities, for 19 fast moving knots and seven quasi-stationary flocculi. In the fast-moving knots, previously unobserved lines of [Ar III], [Ar IV], [Ar V], O I, [O I], [Ca II], and Fe II have been measured, while more stringent upper limits have been set on Hα, Hβ, lines of helium, and lines of nitrogen. In the quasi-stationary flocculi, new lines of [O III], [Fe II], [N I], [N II], He I, [S II], [Ar III], [Ca II], and [O II] have been measured. The results are consistent with earlier investigations, but are more detailed. These results have been employed to infer the physical conditions and abundances in the emitting regions in the second paper of this series.

Subject headings: nebulae: individual — nebulae: supernova remnants

I. INTRODUCTION

The optical nebulosity associated with the Cassiopeia A radio source has been investigated spectroscopically by Baade and Minkowski (1954), by van den Bergh (1971), and by Searle (1971). These spectra show two distinct kinds of emitting regions: the quasi-stationary flocculi (QSFs) have been observed to emit only [N II], Hα, and [O I], while the fast-moving knots are reported to emit in [O I], [O II], [O III], [S II], and [Ar III] with no trace of Hα emission. The QSFs are observed at low velocities (~ 100 km s^{-1}), while the knots form an expanding system with space velocities between 4140 and 8460 km s^{-1} (van den Bergh and Dodd 1970). We have obtained slit spectra of a number of QSFs and knots with the Ritchey-Chrétien spectrograph at the Mayall 4 m reflector at Kitt Peak. These spectra, in the wavelength region 4700–8000 Å, provide new data on the emission lines from Cas A. The data have been reduced to relative fluxes through photographic calibration and observations of NGC 7027. The results have been corrected for interstellar absorption to provide estimates of the relative fluxes emitted at the source. In a companion paper (Chevalier and Kirshner 1977, hereafter Paper II), an interpretation of the new results is presented which considers the possible mechanisms of emission and derives abundances in the emitting gas.

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II. METHODS

a) *The Spectrograms*

Table 1 details the spectrograms used in this investigation. All the spectra were obtained with the Ritchey-Chrétien spectrograph at the Mayall 4 m on Kitt Peak using the 316 line mm^{-1} grating. This gave an approximate reciprocal dispersion of 120 Å mm^{-1}. With the slit set at 160 μm, 1″ in width, we used a decker of length of about 200″. The image-tube plates were recorded on IIIa-J emulsion that had been baked for 4 hours at 65° C in a nitrogen atmosphere. The plates were developed in D-19 along with plates from the same batch that had been exposed for the same length of time in a spot sensitometer.

The slit positions are listed in Table 1 and illustrated in Figure 1 (Plate 10). They were chosen to cross a number of the brightest knots and QSFs.

TABLE 1
SPECTROGRAMS OF CASSIOPEIA A

Serial No.	Kitt Peak No.	Date (1975)	Exposure (minutes)	α (1950)	δ (1950)	P.A.
1................	928	August 13	60	23ʰ21ᵐ19ˢ9	+58°33′49″	118°4
2................	935	August 14	60	23 21 19.9	+58 33 49	39°8
4................	936	August 14	60	23 21 00.1	+58 31 41	131°

b) *Nomenclature*

Because of the large number of individual emission regions observed, and the overlapping emissions at various velocities, the QSFs and knots measured here are best described through reference to Figure 2 (Plate 11). For convenience, the individual regions are denoted in the tables and the discussion by *aQb* for QSFs, where *a* is the spectrogram number from Table 1, and *b* is the label from Figure 1. Similarly, the fast-moving knots are given names *aFb*. In the tables, these labels are connected, to the numbering scheme of Kamper and van den Bergh (1976).

c) *Data Reduction*

The data were reduced using the scheme developed at KPNO by Eric Jensen, as described in Jensen, Strom, and Strom (1976). The spectrograms were scanned in 40 μm × 40 μm steps using the KPNO PDS microdensitometer. The tapes from the PDS were converted from density to intensity through the spot sensitometer plates. The intensity rasters were displayed on the Comtal digital television in the KPNO picture processing laboratory, where Jensen's programs were employed to sum up the intensity from a given knot or QSF. The reduction routine has several features that are of special interest for measuring the line intensities in the spectra of Figure 2. First, the program permits a segment of the spectrogram that is free from regions of emission to be used as a "sky" spectrum, and uses that spectrum together with an estimate of the slit curvature to produce a sky-subtracted raster. In the present case, this removes a large number of night-sky emissions that would otherwise contaminate the regions of interest. Second, the display of the spectrogram permits the region to be measured to be selected very precisely. By choosing the size of the rectangle over which the emission is integrated, a specific segment of a knot can be selected for measurement in every line. A third feature of the reduction routine that proved especially useful was the ability to measure the pixel-by-pixel intensity in a knot to resolve blended lines.

Observations made at the same settings of the spectrograph were obtained of NGC 7027 during the same nights that Cas A was observed. By comparing the instrumental intensities of the emission lines in NGC 7027 with the photometric line ratios measured by O'Dell (1963), the response of the instrument was derived. By using only lines of intermediate strength so that the photographic density-to-intensity conversion was accurate, the derived response curve was smooth and repeated from the first night to the second.

This response curve was used to convert the instrumental intensities into the relative fluxes received at Earth. The next step was to compute the emitted flux, by taking the interstellar absorption into account. We used the value of $A_v = 4.3$ derived by Searle (1971) from the ratio of the auroral to the transauroral lines of [S II] in the fast moving knot filament No. 1. Our assumption of uniform extinction across Cas A will be discussed in Chevalier and Kirshner (1977). By using the Whitford (1956) relation in the form given by Miller and Mathews (1972), we computed the relative flux emitted at the source. Both the line ratios before correcting for reddening, $F(\lambda)$, and after, $I(\lambda)$, are given in Tables 2, 3, 4, 5, 6, and 7. $F(\lambda)$ is not given in Table 2 for the QSFs in which only a small wavelength range is covered. The line ratios in these cases are unaffected by reddening.

We believe that the derived ratios, for lines of intermediate strength, are accurate to 30% in the wavelength range 4700–7300 Å. However, for faint lines that are near the sky brightness, the photographic calibration for the sky subtraction can introduce substantial errors, in addition to the increased uncertainty due to photographic grain noise. Generally, the tendency is to overestimate the strength of weak lines. For very strong lines, the plates are over exposed and the photographic calibration will underestimate the true flux. With those warnings, the derived fluxes are tabulated in Tables 2–7.

The method of normalization chosen for these tables is unusual, as dictated by the unusual spectra of the object. For the QSFs, the units have been chosen so that the sum of the lines [N II] λ6548, Hα λ6562, and [N II] λ6583 has the value 10. This avoids the question of whether the Hα line has been separated from the [N II] lines in exactly the correct way.

For the fast-moving knots, the sum of the [S II] lines at λ6716 and λ6731 has been assigned the value 10. The more common practice of referring line strengths to Hβ makes very little sense where Hβ is not observed!

The relative strengths of the knots and QSFs for a single spectrogram can be estimated from the row labeled "unit of flux." These cannot be compared between spectrograms. Velocities of the fast-moving knots have been derived directly from the rasters and are of relatively low accuracy (± 200 km s^{-1}). The velocities for QSFs have been checked by measurements with a Gaertner measuring engine and should be good to ± 30 km s^{-1}. In any case, the velocity differences over a very small spatial scale are very large, although the spectral differences are not nearly as acute.

In the tables we have noted those nebulosities which have been given a designation by Kamper and van den Bergh (1976). A question mark indicates that there is doubt about the coordinates of the observed feature.

A few obvious difficulties with saturation of the strongest lines in the strongest knots can be observed. For example, in 2F4, the ratio $I(\lambda 5007)/I(\lambda 4959)$ is not near 3, the value from the statistical weights. Generally, though, the line ratios that are known *a priori* are reasonably well reproduced.

III. RESULTS

Although the detailed interpretation of these spectra is deferred to Paper II, a few general remarks are in order. First, the line identifications have been made with reference to supernova remnants (Danziger and Dennefeld 1974) and planetary nebulae (Aller, Bowen, and Minkowski 1955). The presence of more than one

TABLE 2

INTRINSIC LINE RATIOS IN QUASI-STATIONARY FLOCCULI

(Σ N II + Hα = 10, Av = 4.3)

λ (Å)	ID	1Q2 I	2Q2 I	2Q3 I	2Q4 F	2Q4 I	4Q1 I
5755	[N II]	...	...	...	0.10	0.19	...
5876	He I	...	...	...	0.14	0.26	...
6548	[N II]	1.9	2.0	1.4	:2.	:2.	2.0
6562	Hα	1.9	1.7	4.2	:2.	:2.	1.9
6583	[N II]	6.2	6.3	4.4	:6.	:6.	6.1
Unit of flux	...	57.5	78.6	42.4	...	...	56.6
Velocity	...	*a*, −120	+8	−259	...	...	−62
		b, −16	...	...	...	...	...
KB*	...	7	...	...	...	...	22

* From Kamper and van den Bergh 1976.

line from some of the more exotic identifications (for example [Ar V] λ6435 and λ7006) makes these assignments quite reliable. The weak [Fe II] lines, as explained in Paper II, are generally those that have been observed in other nebulae and which are favored by atomic structure. The identifications which seem least secure are O I λ7774 and Fe II λ7376 (in 2F4), which are near the plate limit. The λ7774 line has been observed in the Orion Nebula along with other permitted lines of O^0 (Andrillat and Houziaux 1968; Morgan 1971; and Grandi 1975). The λ7774 line is the only quintet line observed in Orion, and it is fainter than many of the triplet lines. If the permitted lines were formed in recombinations, the λ7774 line should be a factor 5/3 brighter than the λ8446 line, which is the brightest of the triplet lines. Combined with the fact that $I(\lambda 8446)/I(\lambda 7330 + \lambda 7320) < 2 \times 10^{-4}$ if recombinations dominates whereas the ratio is observed to be about 0.1, this rules out recombinations as the source of the permitted lines in the Orion Nebula. This has led to the investigation of H Lyman-line fluorescent mechanisms. These fluorescent mechanisms are probably not important in the fast knots because little or no H is present (see Paper II). The fact that the λ7774 line is the only O I line observed is consistent with its being formed in recombinations. The triplet λ8446 line, which is outside of the wavelength region we observed, should be 3/5 as bright as the λ7774 line and will provide a future test of the identification. An estimate of the ratio I(O I λ7774)/I([O II] λ7320–7330) in the recombination case (Andrillat and Houziaux 1968) shows that the temperature of the emission region must be about 5000 K to produce the observed ratio of 0.017. This is cooler than the

TABLE 3

LINE RATIOS IN STRONG QSFs

(Σ N II + Hα = 10, Av = 4.3)

λ (Å)	ID	1Q1 F	1Q1 I	2Q1 F	2Q1 I
4861	Hβ	0.07	0.34	< 0.6	< 2.8
4959	[O III]	< 0.05	< 0.2	< 0.5	< 2.1
5007	[O III]	0.04	0.17	< 0.5	< 1.9
5159	[Fe II]	0.04	0.1	...	...
5200	[N I]	0.04	0.11	< 0.5	< 1.4
5527	[Fe II]	0.03	0.07	...	...
5755	[N II]	0.19	0.37	< 0.4	< 0.7
5876	He I	0.11	0.21	< 0.3	< 0.6
6300	[O I]	0.49	0.58	< 0.3	< 0.4
6364	[O I]	0.17	0.19	< 0.3	< 0.4
6548	[N II]	1.9	1.9	3.0	3.0
6562	Hα	2.3	2.3	2.7	2.7
6583	[N II]	5.8	5.8	4.3	4.3
6678	He I	0.03	0.03	...	...
6716	[S II]	0.04	0.04	0.7	0.6
6731	[S II]	0.12	0.11	0.7	0.6
7065	He I	0.04	0.03	...	...
7136	[Ar III]	...	...	0.7	0.5
7155	[Fe II]	0.13	0.09	0.12	1.0
7291	[Ca II]	< 0.16	< 0.1	0.42	0.29
7320–7330	[O II]	0.34	0.21	1.3	0.80
Unit of flux	...	...	739.	...	72.8
Velocity	...	...	+41	...	−179
KB	...	...	10?	...	19

TABLE 4

LINE RATIOS IN FAST KNOTS: SPECTRUM 1

(Σ S II = 10, Av = 4.3)

λ	ID	1F0		1F1		1F2		1F3		1F4		1F5		1F6		1F7	
		F	*I*	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*
4959..........	[O III]	...	...	3.2	15.	5.3	25.	25.	120.	1.1	5.2	6.4	30.	1.2	5.7	1.7	8.
5007..........	[O III]	6.9	31.	18.	83.	17.	76.	133.	600.	5.8	26.	13.	61.	3.1	14.	6.4	29.
6300..........	[O I]	3.1	4.1	2.6	3.4	1.2	1.6	41.	54.	1.1	1.5	3.0	4.0	0.4	0.5	1.0	1.3
6364..........	[O I]	...	...	...	...	0.7	0.9	17.	21.	0.5	0.6	0.9	1.2	...	...	...	...
6435..........	[Ar V]	...	...	...	...	...	...	...	...	...	...	0.03	0.03	...	...	...	...
6562..........	Hα	...	...	...	...	< 0.2	< 0.2	...	...	...	...	< 0.04	< 0.05	...	...	...	...
6716..........	[S II]	4.1	4.1	3.2	3.2	10	10	3.9	3.9	5.2	5.2	3.7	3.7	4.0	4.0	3.8	3.8
6731..........	[S II]	5.9	5.9	6.8	6.8			6.1	6.1	4.8	6.3	6.3	6.3	6.0	6.0	6.2	6.2
7005..........	[Ar V]	...	...	...	...	0.28	0.24	...	...	...	...	0.12	0.10	...	...	...	...
7136..........	[Ar III]	...	...	...	...	1.6	1.3	...	...	...	...	1.5	1.2	...	...	...	...
7320–30.......	[O II]	2.4	1.7	6.1	4.3	8.8	6.2	229.	160.	1.4	1.0	9.1	6.4	1.9	1.3	3.0	2.1
7751..........	[Ar III]	...	...	...	...	:0.6	:0.3	...	...	...	...	:0.4	:0.2	...	...	...	...
Unit of flux...	...	...	31.3	...	16.2	...	268.5	...	13	...	77.6	...	1004	...	66.5	...	36.9
Velocity (km s^{-1})....	...	+2366		+323		+1207		...		+2923		+561		+2547		+2040	
KB..........	...	...		...		59		...		...		93		100		...	

TABLE 5

LINE RATIOS IN FAST KNOTS: SPECTRUM 2

(Σ S II = 10, Av = 4.3)

		2F1		2F2		2F3		2F5		2F6	
λ	ID	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*
4959...........	[O III]	...	...	1.7	7.9	10.	47.	...	...	...	...
5007...........	[O III]	...	...	5.3	24.	32.	143.	...	...	...	...
6300...........	[O I]	...	...	1.4	1.8	9.8	13.	2.0	2.6	...	...
6364...........	[O I]	...	...	0.4	0.51	...	...	...	...	...	...
6716...........	[S II]	4.4	4.4	4.3	4.3}	10	10	{6.1	6.1	6.2	6.2
6731...........	[S II]	5.6	5.6	5.7	5.7}			{3.9	3.9	3.8	3.8
7136...........	[Ar III]	...	...	1.5	1.2	...	...	...	...	...	...
7320–30........	[O II]	...	...	3.3	2.3	96.	67.	4.3	3.0	...	...
Unit of flux.....	...	...	45.6	...	96.0	...	13.3	...	...	30.1	11.2
V (km s^{-1}).....	...	+3382		+3517		−4730		+3842		~0	
KB...........	...	...		...		18				...	

temperatures normally found in photoionized regions, but it is reasonable for the temperature in the recombination region behind a cooling shock wave. As discussed in Paper II, the line intensities in the fast knots indicate that emission excited by shock waves is observed.

The Fe II λ7376 identification is uncertain because of its proximity to the [O II] λλ7320–7330 doublet. We decided against the [O II] identification because there is no emission in other lines at the same velocity.

Although there is some overlap of QSFs and knots along the slit, the velocity differences make the two spectra distinct. In some cases, velocity shear within a single knot is very large. The shear in "filament No. 1" (our 1F5) is well known (van den Bergh 1971). In our spectrum 4 the velocity differences seen in [S II] are those of an expanding shell with a velocity separation of 2500 km s^{-1} along the line of sight. (An unfortunate blemish of tube background makes this shell appear deceptively complete.) In these cases, the marked locations of the knots on Figure 2 can be used to determine the region of the knot for which the line ratios were determined and for which the radial velocity is given. Generally, the line ratios do not seem to be a strong function of radial velocity in a given knot.

As remarked by Kamper and van den Bergh on the basis of photographs taken through interference filters, there are some knots which are much stronger in oxygen lines than in sulfur. This variation in the oxygen/sulfur ratio is apparent in Table 5 where it can be seen that 2F3 has a [O II] λ7320–7330/[S II] λ6716–6731 ratio that is roughly 30 times larger than is seen in 2F2 or 2F5.

The diffuse [S II] emission noted in Kamper and van den Bergh is quite visible in spectrum 2. The observed ratio $I(\lambda6716)/I(\lambda6731)$ is 1.7.

We believe that the data presented here are near the limit of what can be done photographically. However, we also believe that important line measurements which are either uncertain in this investigation or just below the detection threshold are of considerable theoretical importance (see Paper II). Future investigations will presumably be undertaken with linear detectors which have larger dynamic ranges. However, the very large number of picture elements in the present data, which permits a large area to be taken

TABLE 6

LINE RATIOS IN FAST KNOTS: SPECTRUM 4

(Av = 4.3, Σ [S II] = 10)

		4F2		4F3		4F4		4F5		4F6	
λ	ID	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*	*F*	*I*
4959...........	[O III]	...	...	3.0	14.	4.9	23.	...	...	...	...
5007...........	[O III]	1.5	6.9	11.	49.	13.	60.	...	...	...	...
6300...........	[O I]	2.0	2.6	?0.7	?0.9	3.3	4.4	...	...	...	...
6364...........	[O I]	...	...	0.60	0.76	1.2	1.5	...	...	...	...
6716...........	[S II]	2.5	2.5	4.0	4.0	3.3	3.3	5.0	5.0	5.0	5.0
6731...........	[S II]	7.5	7.5	6.0	6.0	6.7	6.7	5.0	5.0	5.0	5.0
7136...........	[Ar III]	...	...	1.2	0.93	4.8	3.8	...	...	...	...
7320–30........	[O II]	11.	7.6	12.	8.3	37.	26.	...	...	...	...
Unit of flux.....	...	37.2		63.3		90.5		20.		26.	
V (km s^{-1}).....	...	+4089		−606		+1071		+1380		~0	

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TABLE 7

RELATIVE FLUXES IN 2F4

λ	ID	F(obs)	$I(A_v = 4.3)$
4740..........	[Ar IV]	0.11	0.68
4861..........	Hβ	<0.03	<0.16
4959..........	[O III]	5.41	25.3
5007..........	[O III]	9.29	41.8
5192..........	[Ar III]	0.08	0.29
5577..........	[O I]	0.10	0.25
6300..........	[O I]	4.16	5.49
6364..........	[O I]	1.68	2.13
6435..........	[Ar V]	0.06	0.08
6562..........	Hα	<0.04	<0.04
6716..........	[S II]	10.0	10.0
6731..........	[S II]		
7006..........	[Ar V]	0.32	0.27
7136..........	[Ar III]	5.54	4.38
7291..........	[Ca II]	0.29	0.21
7320–30.......	[O II]	16.3	11.4
7376..........	Fe II	0.09	0.06
7751..........	[Ar III]	1.78	0.98
7774..........	O I	:0.3	:0.2
Flux unit......	...	...	1267
Velocity.......	...	...	−1836
KB...........	...	...	(72?)

as "sky" and which allows the individual knots to be separated from the overlapping QSFs, even if they have large velocity shear, will be hard to duplicate.

We would like to thank Howard French, Eric Jensen, and S. van den Bergh, for their cooperation in this work.

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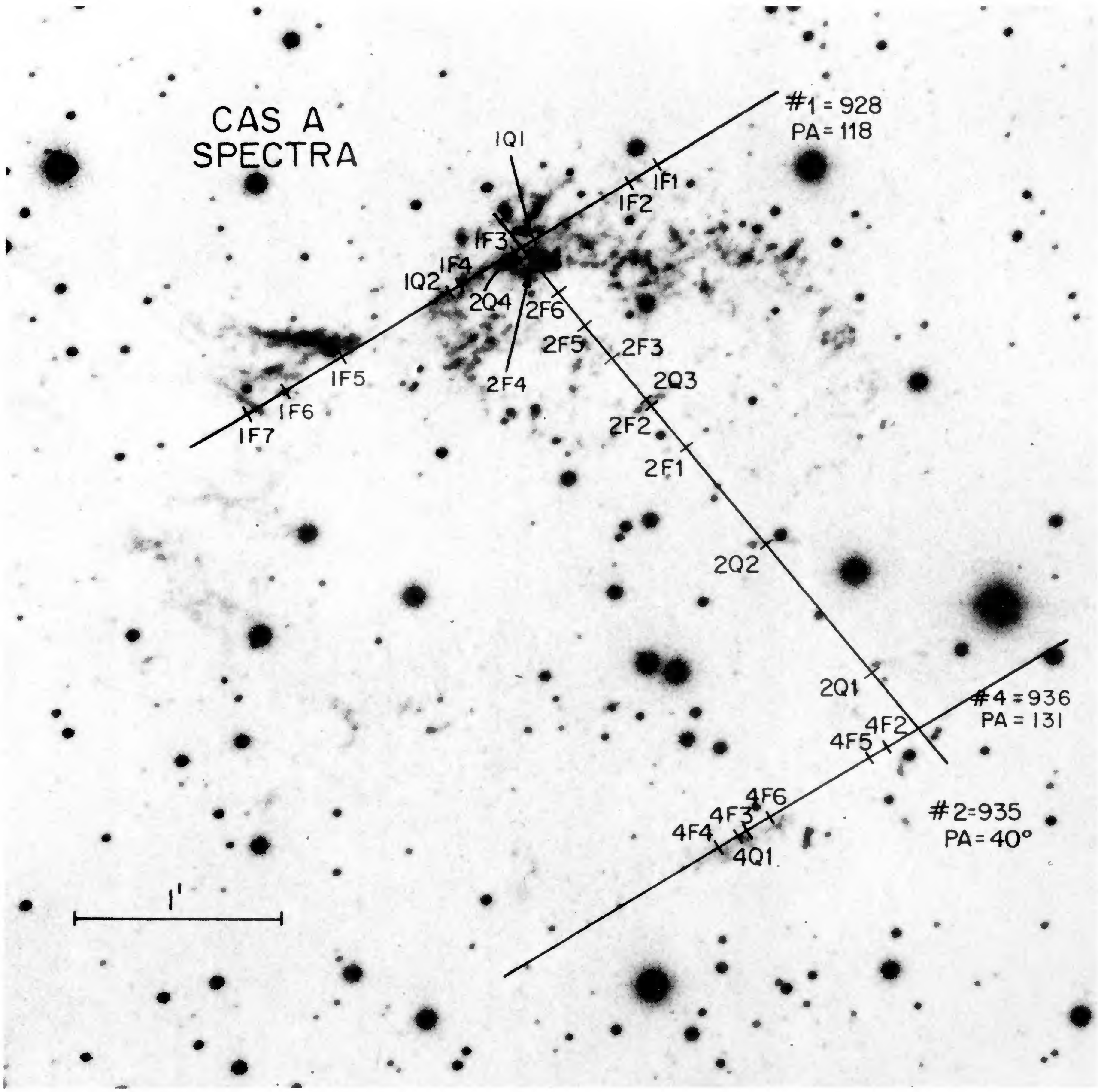

FIG. 1.—The approximate slit positions used in this investigation are here shown superposed on a recent broad-band red photograph kindly provided by S. van den Bergh. Approximate locations of the individual knots and QSFs are indicated. North is to the top, and east is to the left.

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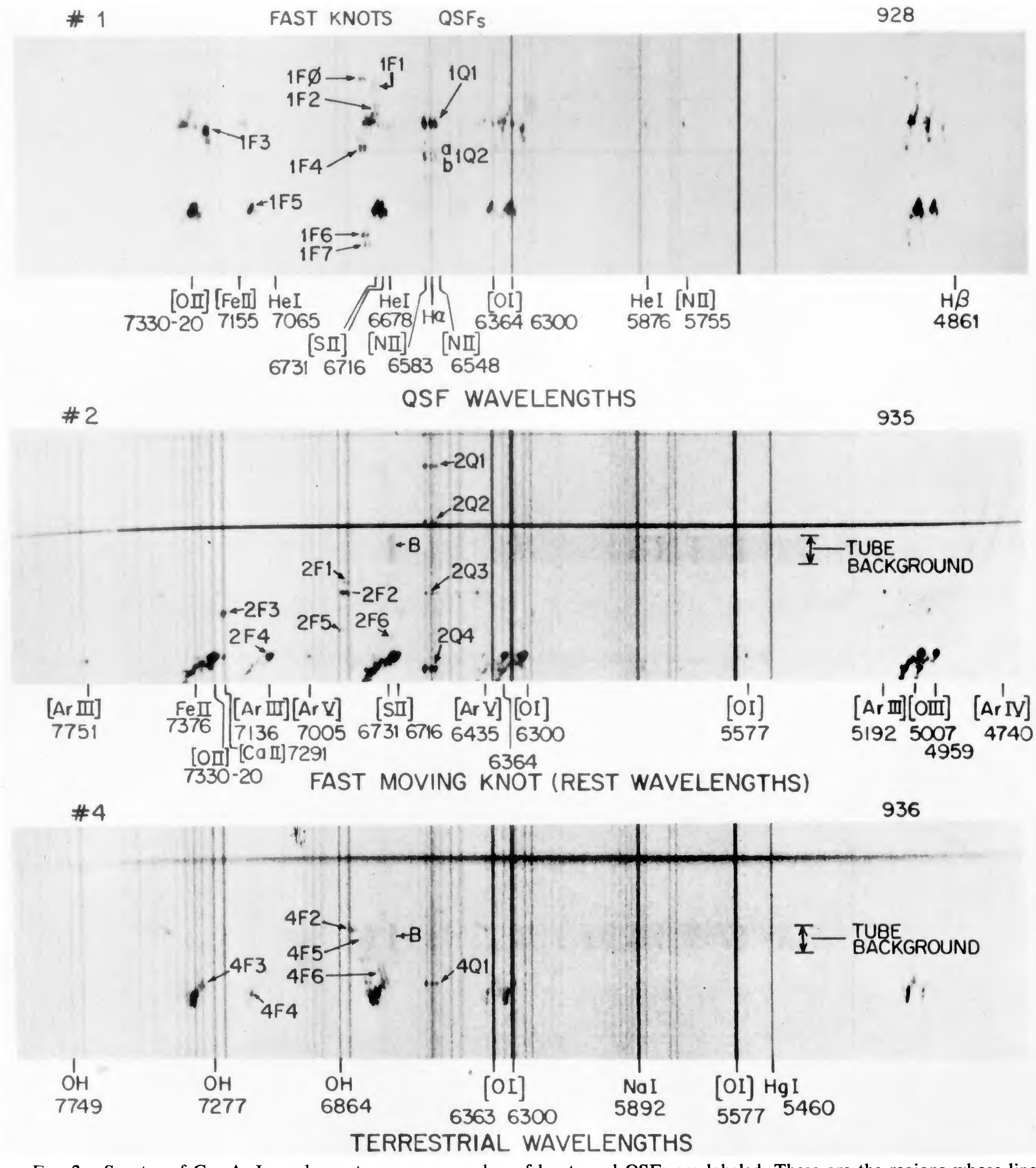

FIG. 2.—Spectra of Cas A. In each spectrogram, a number of knots and QSFs are labeled. These are the regions whose line ratios have been measured, and which are listed in Tables 2–7. A number of characteristic lines have been indicated. Adjacent to spectrum 1, the wavelengths of lines that have been found in QSFs have been labeled. Next to spectrum 2 some of the lines seen in the fast-moving knots are shown. In spectra 2 and 4, the central region marked "tube background" shows the residual effects of the earlier use of the spectrograph on a bright nova. The line marked B belongs to the background and not to Cas A. Below spectrum 3, the wavelengths of some prominent terrestrial lines are given. In the data reduction (described briefly in the text), the night-sky spectrum is subtracted from the entire raster so that the derived line ratios are not contaminated by night-sky emission.

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