A METHOD TO MEASURE THE NIGHT SKY LUMINOSITY

SALVATORE CRISTALDI, SEBASTIANO FOTI
Istituto di Astronomia, Università di Catania, viale A. Doria 6, I-95125 catania, Italy

1. Introduction

The progress of knowledge has led Man to increasingly appreciate the natural resources and thus to pose the question on their better exploitation. Also in the case the electric energy used for outdoor lighting, many protests have been raised against light pollution, which is a source of waste of energy and a cause of serious damage for the cultural life of citizens who cannot enjoy the view of the starry sky.

While the evaluation of the cultural damage needs long times and is subject to different opinions, the economic damage can be evaluated through the objective measures of the artificial radiation scattered back from sky to Earth.

In 1990 the first of us decided to study the light pollution in the area of Catania, proposing to the other, at that time undergraduate student of physics, to investigate this subject in his thesis and suggested the method we are going to explain.

2. Description of the method

The procedure consisted in taking photos of the vault of heaven, with a camera on which an optical fish-eye system had been mounted, capable of widening the field of view to about 180°.

The device for the data acquisition, made by the second of us, was very simple.
1) The camera's support was made of a rigid plate, about 40-cm in diameter, with three screws and two levels for its setting (perpendicular to the vertical of the observing site). A metallic tube with a diameter of 2 cm and about 30 cm long, was mounted on the edge of the plate and perpendicular to it. On the upper end was a 0.2 x 5 cm longitudinal translucent slit, turned towards the plate's axis to which it was parallel. Inside of it a 2.5 V, 0.5 A. battery-feeded lamp was placed. The switching of the lamp was made by an external button. With respect to the plate, the lower part of the slit had the same height of the entrance pupil as that of the acquisition system being described.
2) The acquisition system consisted in a camera with a focal lenght of 50 cm on which a Kenko objective, estending the field of view to the whole emisphere towards which is directed, had been mounted. A small square, mounted at the center of the plate, allowed the camera to be mounted on it, so that its optical axis was perpendicular to the plane

of the plate itself and turned towards the emisphere over it.
3) To orientate the plate, a compass was used so that the cylinder of point (1) was directed towards North, with respect to the optical axis of the camera.

The image of the vault of heaven provided by the equipment just described, consists in a disc with a diameter of 20 mm. A Technopan 2415 film by Kodak was used to acquire it. The optical system, as we said, covered a field of about 180°, whose image resulted, on the focal plan, in the orthogonal projection of the semi-space in front of the entrance pupil of the system.

As we had to take photometric measurements on the images so obtained, we first checked that the optical devices did not alter, varying the height and azimuth of observation, the relations of luminous fluxes received. To this aim, we used an arch forming a semi-circumference with a radius of 500 mm, made of a blacken sheet-aluminum, where some holes, 7-mm in diameter, were made along its longitudinal axis, in such a way that, putting the arch in a vertical position, the centres of the holes corresponded to the zenith distances of 0, 15, 30, 45, 60, 65, 70, 72.5, 75, 77.5, 80, 81, 82, 83 degrees. Each of these holes hosted a little cylinder with inside a little lamp of 3.5 V., 0.5 A. linked to a regulated power supply. In front of the little lamp the cylinder was closed by a diffuser, which was externally shielded by a thin diaphragm with a diameter of 3 mm: this part of the cylinder had a diameter such that it tightly inserted into the holes of the aluminum arch and the external surface of the diffuser aligned with the concave side of the arch. We first set the camera so that the center of the entrance pupil of the Kenko device coincided with that of the arch; then we made the optical axis center the hole at a zenith distance of 0°, we stabilized the little lamp, and at last we performed a 1/60 sec exposure. This procedure was repeated, moving the cylinder each time to a different hole of the arch. Then we moved the azimuth of the arch by 90°, with respect to the camera and repeated the operation. The measures, made from the negatives obtained by Foti and performed with a digital 12-bit microdensitometer, showed that the transmittance of the optical system, presented deviations of about 7% with respect to the mean transmittance. Since the precision estimated for our measures was 10%, we considered the measures of intensity derived from the negatives independent from the values of height and azimuth of the sky area they referred to.

To tackle the problem of studying the light pollution in the area of Catania, we decided to exploit the town location, lying Catania in a semicircle from N-E to S-W towards West and being surrounded by the sea at East. The measures were then scheduled along the following directions: N-E, N, N-W, and S-W, starting from the center of the town coinciding with the Astrophysical Observatory on S.Sofia hill inside the University Campus. The W direction was not included due to the presence of the highway Catania-Palermo. We decided to set the surveying points along the above-mentioned directions at a distance of about 8, 16, and 24 km from the center of the town (see Fig. 1).

For the observations made by Foti on moonless nights (see Tab 1.), we selected a place in each site chosen for the observations, not much disturbed by the local lights or by traffic, where we mounted the equipment. The camera with the optical system was mounted on the proper little square of the plate. This one was then put in horizonthal position and set so that the tube with the slit was oriented towards N direction with respect to the optical axis of the camera. At least two hours after the sunset or three hours after the dawn, we performed a 50 min exposure using a 2415 Kodak Technopan film. During the first 10 sec. of the exposure the slit on the tube was illuminated so that it was easy to find the North direction indicated by the image of the slit on each obtained negative. We carried out the exposures in the 13 sites using a film of the same kind on which we obtained the image of a scale of grey illuminated by a stabilized puntiform source. (It would be convenient to perform this procedure with the same film used to record the sky images, obtained in the various places).

All the negatives obtained, except that derived from the scale of grey, were scanned with the PDS of the Trieste Astronomical Observatory, using a 20x20μ window. The scale of grey and the obtained negative were measured with a digital 12-bit microdensitometer of the OACT. These measures were used to derive the caracteristic curve of emulsion. The flaws due to the emulsion's crack and to the dust deposited on the surface of the digitalized images were removed. These irregularities would have altered the real dynamics of the digitalized images. The caracteristic curve of the emulsion, as for the part comprising the range of densities found on the negatives obtained in the 13 points of surveys, was verified, with $\chi^2 = 4.521E^{-5}$, by a polynom of seventh degree, then used for the conversion into intensities of the measured densities.

Since the values of the intensities so obtained were expressed in arbitrary units, photogram by photogram, it was necessary to unify the units and then convert it in absolute units. This was performed by taking as a reference the trail of the α Bootis present in the photograms obtained in the places of survey. As we had to measure the luminosity of the sky, we did not consider the flux of the star outside the atmosphere but the flux which reached the Earth. To obtain this flux we had to determine the magnitude of α Bootis, both over and below the atmosphere, in the spectral band limited by the transmittance of the optics and by the spectral sensibility of the emulsion used. Then we determined the coefficent of atmospheric estinction in the spectral band used by us. To this aim Foti spent an entire observing night performing 11 exposures, each lasting 5 min. The first and the last three exposures were taken every 30 min., while the other were taken every 60 min.; this was done so that the observations were better distributed with respect to the masses of air respectively crossed. In this case, since the observations of the sky luminosity and the absorption coefficient were not determined simultaneously, we had to derive the latter using the trails of the star α Tauri instead of those of α Bootis, present in the photograms relative to the various places, because in the mean time, α Bootis had became visible for an insufficient period of time. However all the exposed photograms were developed contemporarly in the same process.

The images digitalized in transparency, after removing the effects of the emulsion crack and dust, were then converted into intensity through the polynomial derived from the caracteristic curve. In the IDL environment, the images were reduced to the 500x500 pixel size and after the noise has been subtracted and a smoothing of 3x3 pixel performed, the isophotes were traced. The images so obtained are shown in Figs. 2-14.

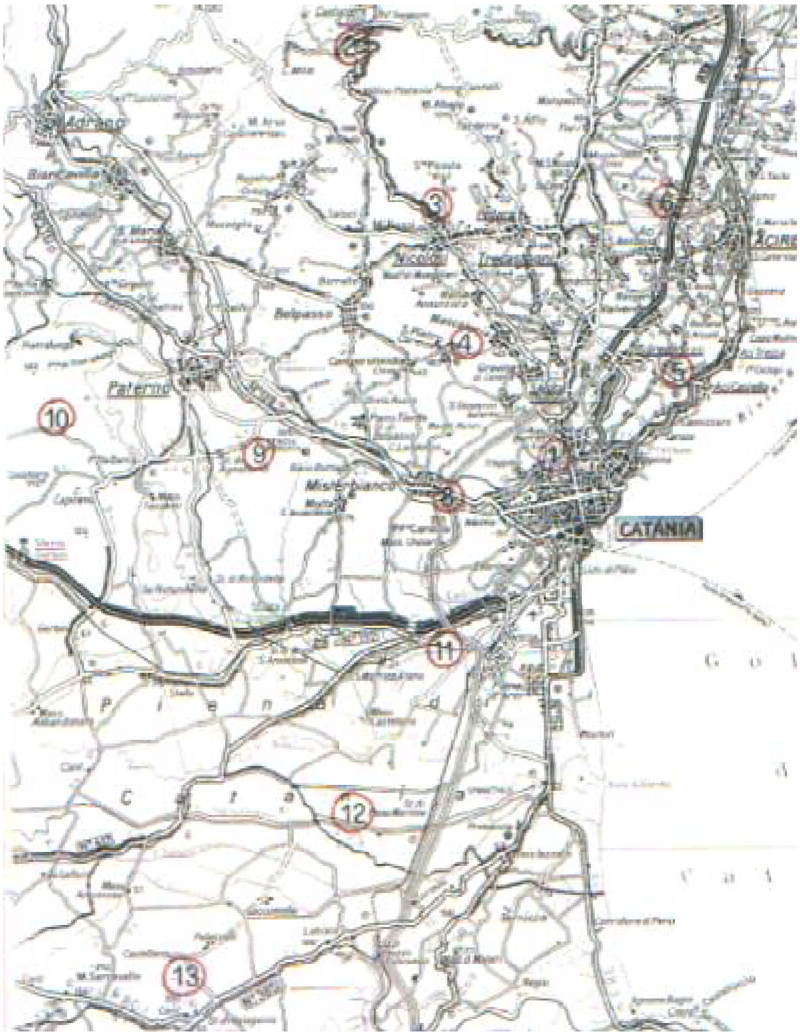

Fig. 1. Map of the region where the measurements were carried out.

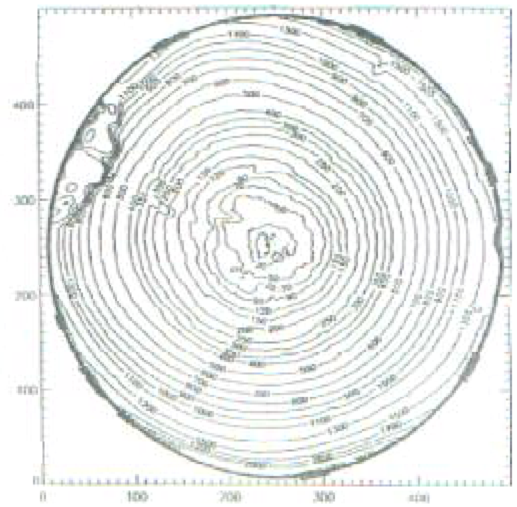

Fig. 2. 11/20/90-Catania (Univ.Campus S.Sofia).Height a.s.l. 195 m.

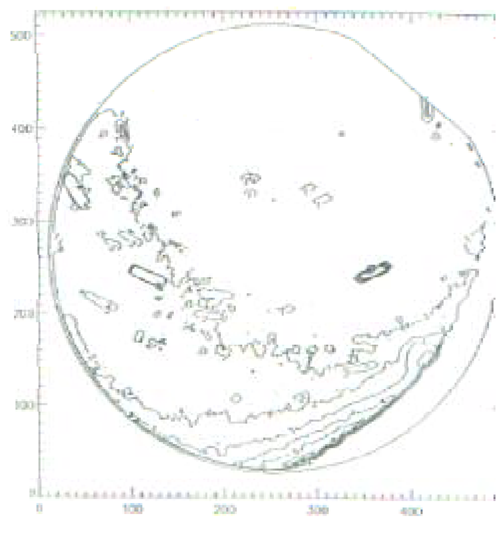

Fig. 3. 05/07/91-Serra La Nave. Height a.s.l. 1700 m.

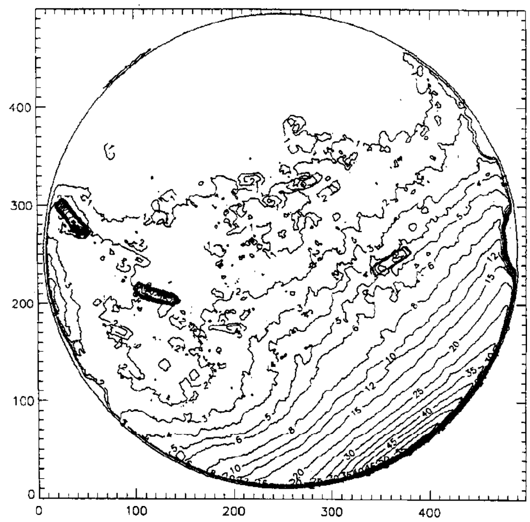

Fig. 4. 05/08/91-Mount Nocilla. Height a.s.l. 900 m.

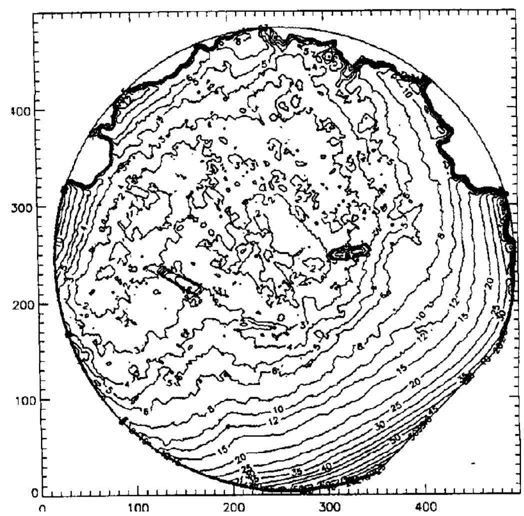

Fig. 5. 06/08/91-Schimmicci district. Height a.s.l. 390 m.

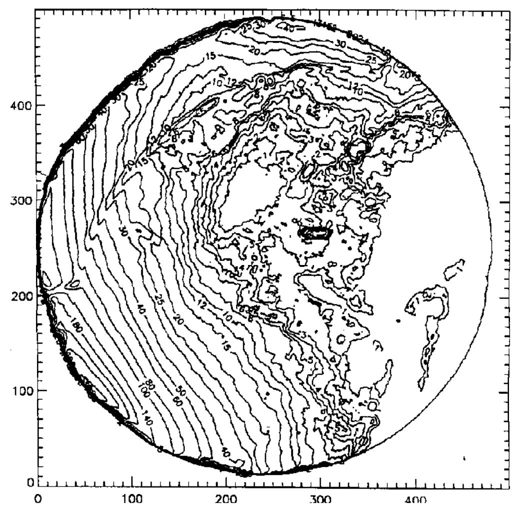

Fig. 6. 06/13/91-Reitana district. Height a.s.l. 170 m.

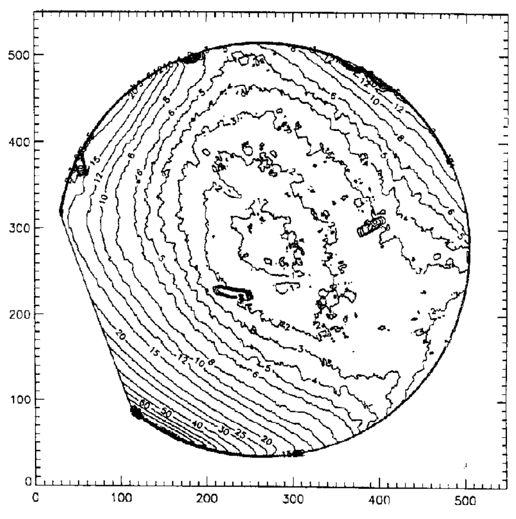

Fig. 7. 06/10/91-Ramondetta district. Height a.s.l. 350 m.

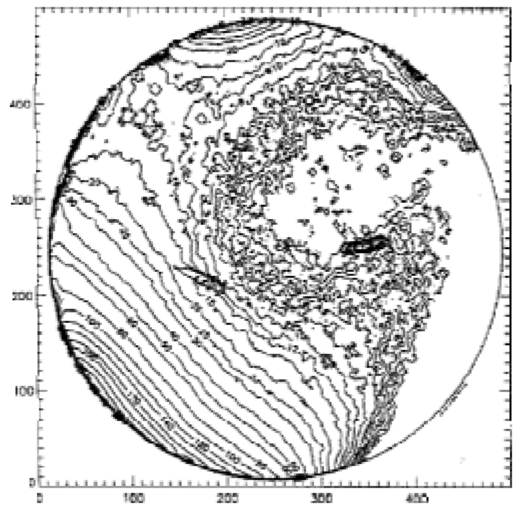

Fig. 8. 06/15/91-S. Anna district. Height a.s.l. 20 m.

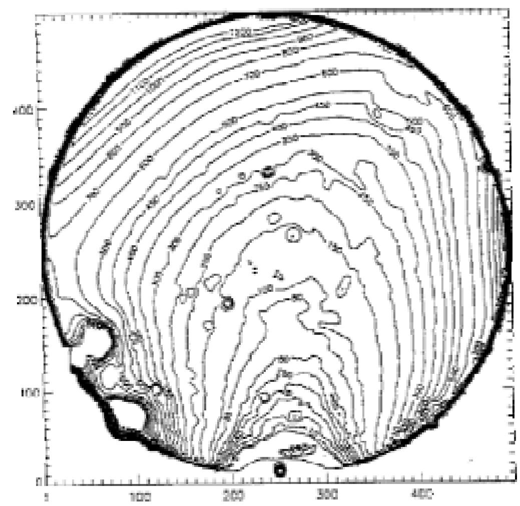

Fig. 9. 07/13/91-Misterbianco (ring-road East). Height a.s.l. 160 m.

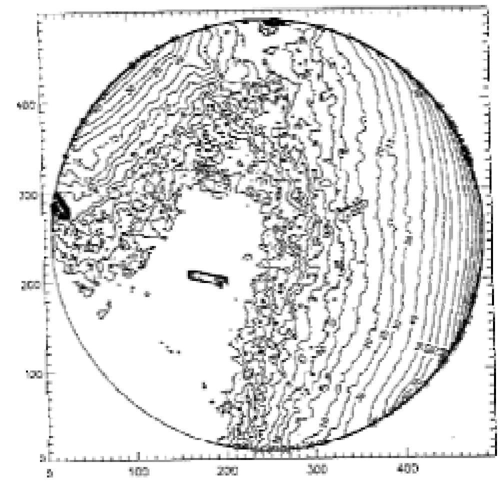

Fig. 10. 07/03/91-Bottoga district. Height a.s.l. 200 m.

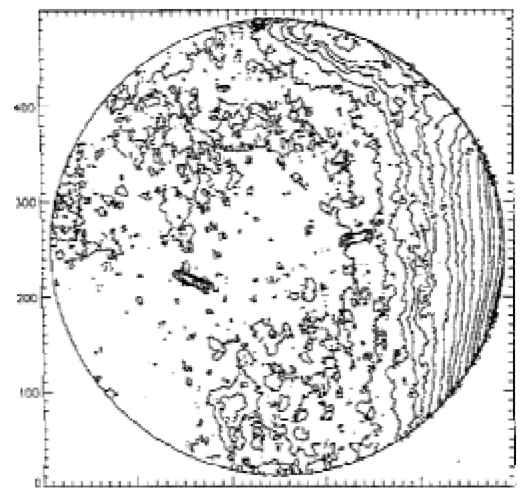

Fig. 11. 07/10/91-Irmana district. Height a.s.l. 130 m.

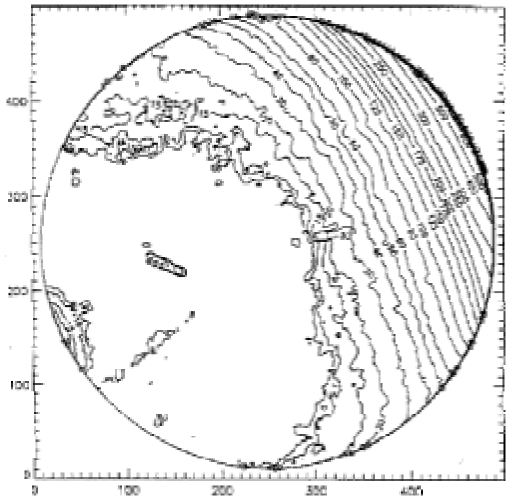

Fig. 12. 07/14/91-Gelso Bianco district. Height a.s.l. 20 m.

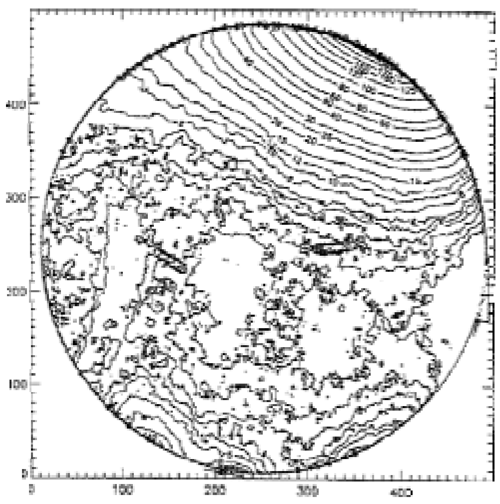

Fig. 13. 07/12/91-Robavecchia district. Height a.s.l. 15 m.

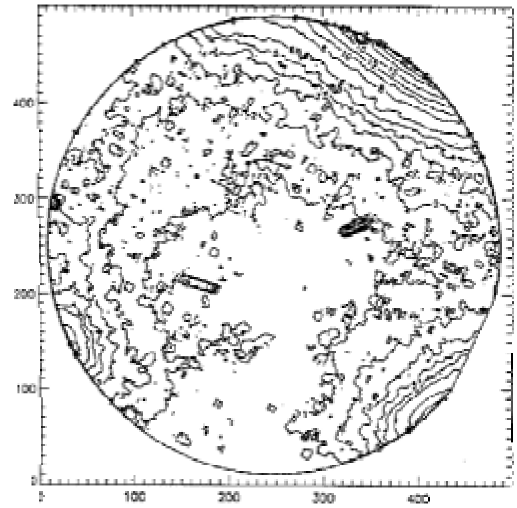

Fig. 14. 07/05/91-Catalicciardo district. Height a.s.l. 50 m.

In Figs. 2-14 the numbers reported on the isophotes show the measure at earth of the flux coming from the zone of sky in arbitrary units. For each direction considered, the trend of the intensity at the zenith relative to a unitary solid angle, is reported as a function of the distance from the center of Catania in Tabs 2-5 and Figs 15-18.

The mean fluxes measured between the two adjacent isophotes are reported in Tabs 6-17 for each place as a function of the zenith distance towards the Catania direction. These data are reported in Figs 19-30.

As we could not obtain the data relative to the power of energy provided by the electric company and to the lamps used in the various municipal lands involved in our survey, we could not take into consideration the contribution the light of each inhabited center to the pollution produced by the town of Catania. We only knew the datum of the power emitted, 7914.5 Kw, provided by Mr. Marino (Ufficio tecnico della Pubblica Illuminazione) who is kindly acknowleged. Due to above-mentioned difficulties, we decided to derive only the pollution produced in the town of Catania. We considered the measures made along the direction SW (Catania-Scordia), where there are only scarsely illuminated areas, and the scattered flux measured in this direction. In Fig 31 the logarithms of these fluxes, detected in the involved areas are reported as a function of their distance from Catania. The linear relation so derived is reported in the same figure. Using this relation we obtained the flux scattered in the circle with a radius of 0.5 km., and in the circular coronae, all 1 km wide and with radius from 1 to 28 km, centered at the Observatory.

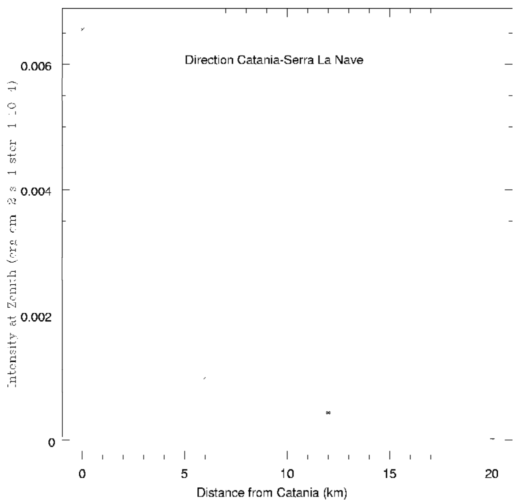

Fig. 15. Direction Catania-Serra La Nave.

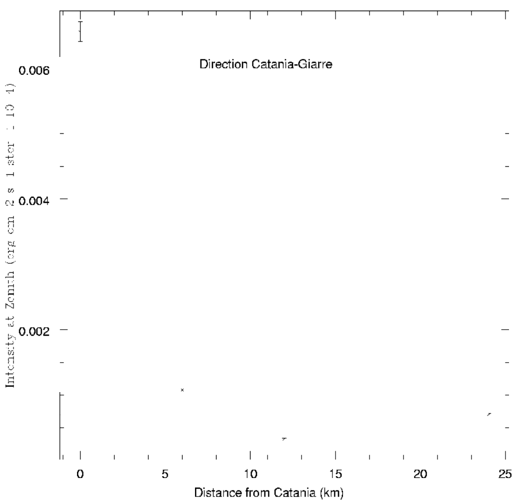

Fig. 16. Direction Catania-Giarre.

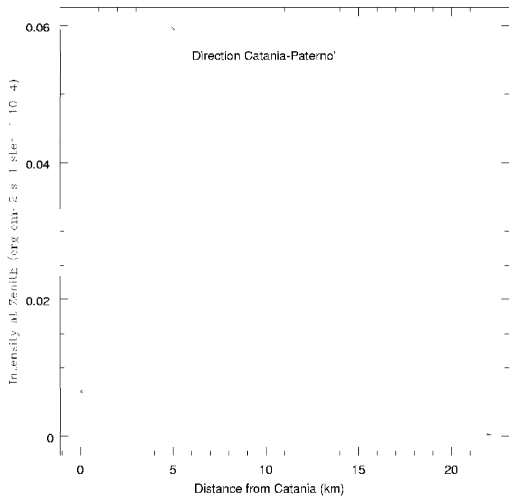

Fig. 17. Direction Catania-Patern.

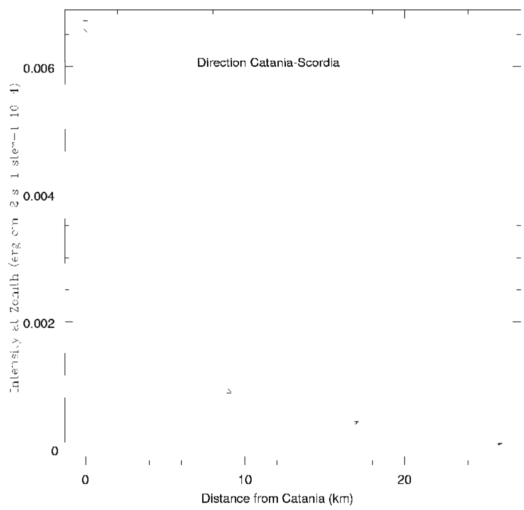

Fig. 18. Direction Catania-Scordia.

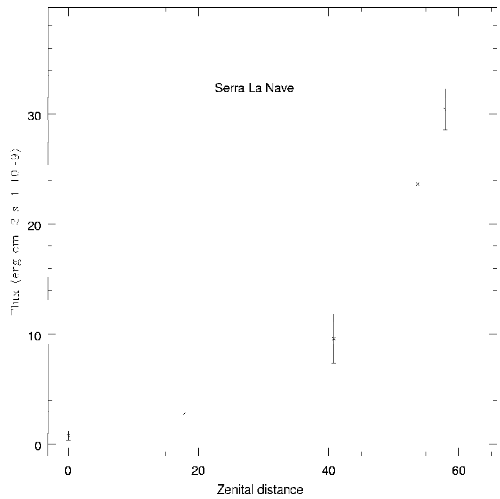

Fig. 19. Serra La Nave.

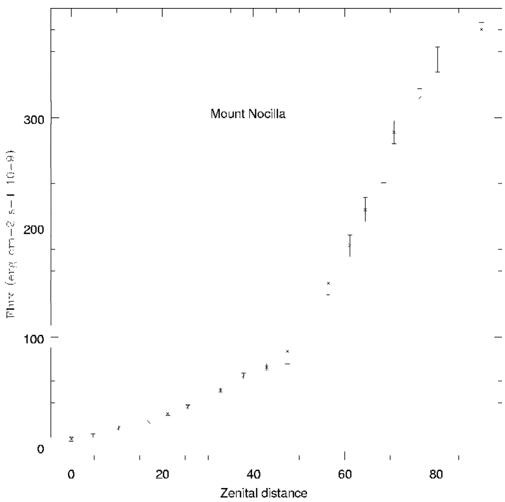

Fig. 20. Mount Nocilla.

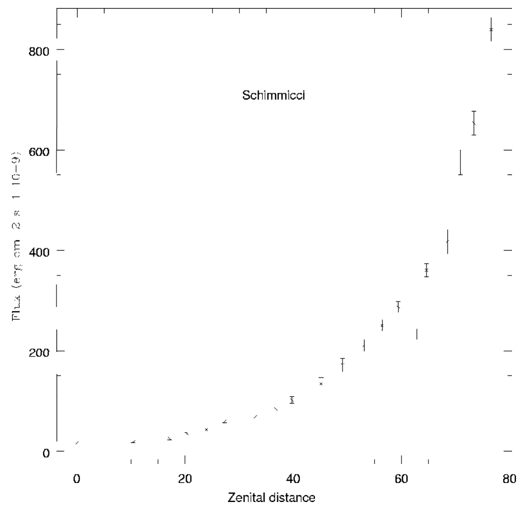

Fig. 21. Schimmicci district.

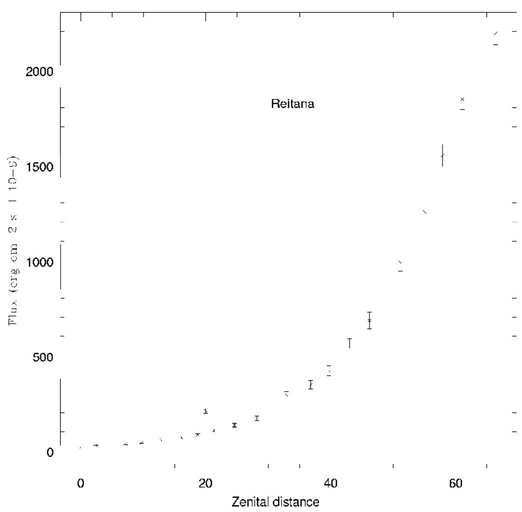

Fig. 22. Reitana district.

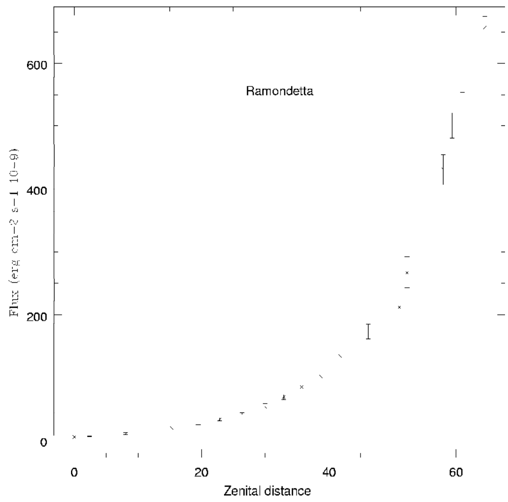

Fig. 23. Ramondetta district.

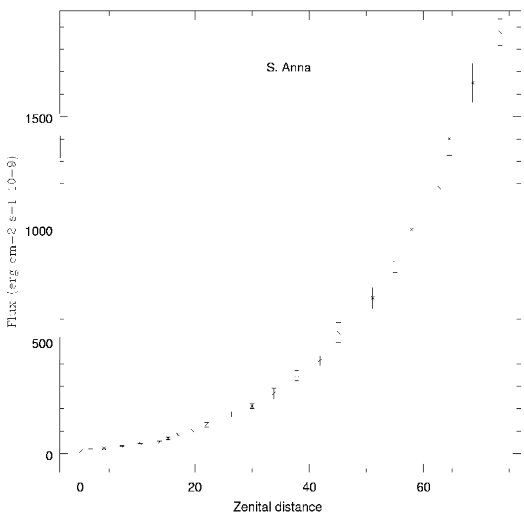

Fig. 24. S. Anna district.

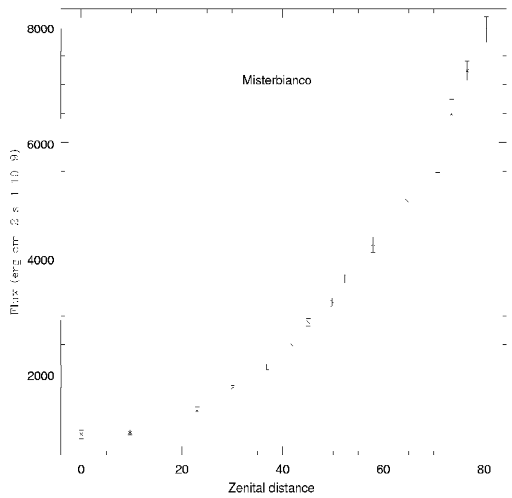

Fig. 25. Misterbianco (ring-road East)

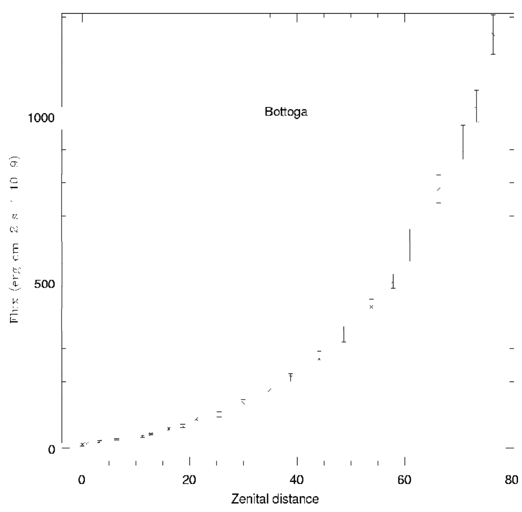

Fig. 26. Bottoga district.

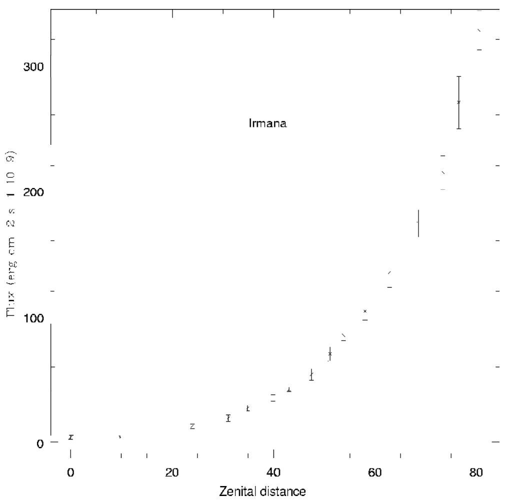

Fig. 27. Irmana district.

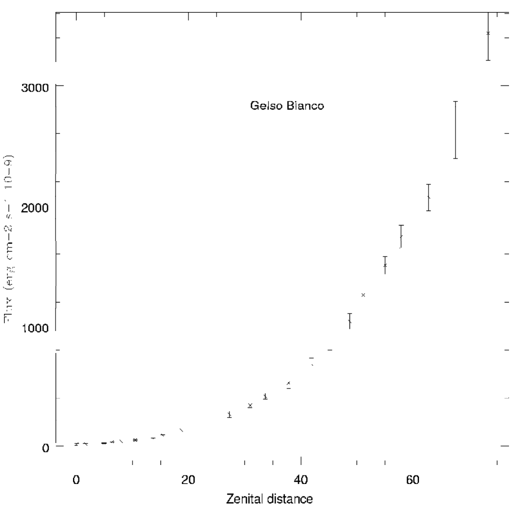

Fig. 28. Gelso Bianco district.

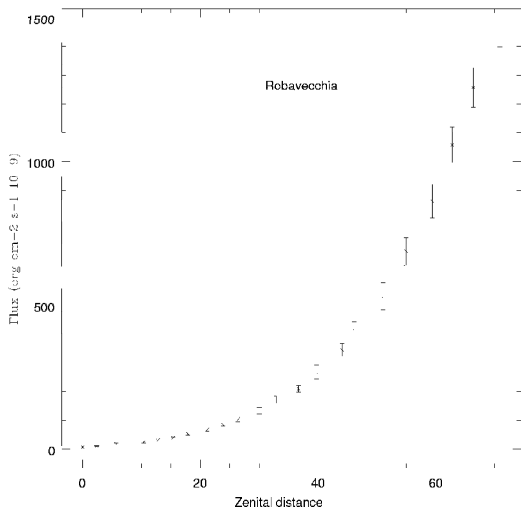

Fig. 29. Robavecchia district.

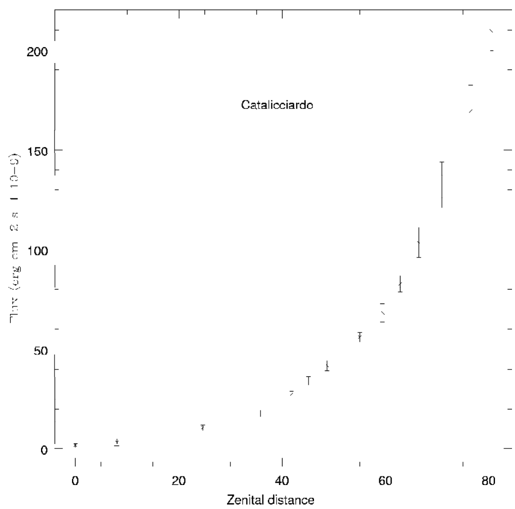

Fig. 30. Catalicciardo district.

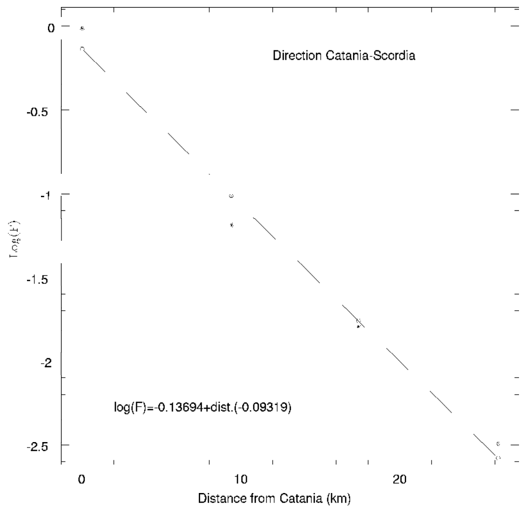

Fig. 31. Direction Catania-Scordia.

Taking the flux scattered in the Morgan and Johnson's V band, we obtained for an area having a radius of 28 km a luminous flux of 1535907 lumen, corresponding to 22573 w. To derive the radiation emitted in the upward emisphere from the lighting devices, from the measure of the artificial radiation detected at earth with the above- mentioned device, we assumed that 10% of the direct radiation towards the sky was reflected from sky to earth. Taking into account the effective power emitted in Catania (0.8% of the nominal power), the mean efficiency of the lamps mounted, corresponding to 14.1% and the scattering coefficient of 10 %, we calculated that the value of 22573 w, concerning the flux scattered in the area around Catania having a radius of 28 km, imply that 24% of the power employed for the outdoor lighting of this town is sent toward the sky. This method could be more efficient using a CCD as a detector which would simplify the acquisition and the data analysis.

By examining the graphs and tables obtained from our measurements one can note the deviation from the general trend of each graph and data, due to the local contributions to the general lighting pollution caused by the lights of Catania. The photographs of these areas would allow us to study the lighting pollution but it would be necessary to know the features of all the lighting systems of a given area.

Acknowledgements

We would like to express our thanks to the Directors of the Catania Astrophysical Observatory and Trieste Astronomical Observatory for letting us use the research facilities. We are also indebted to P. Massimino for his help in the electronic processing and D. Recupero for the English translation.

Table 1 - Places and times of the observations.

N	Place	Height.m	Dist.km	Date	C.E.M.T.
1	Univ. Campus, S.Sofia.	195	0.0	11/20/90	17 50
2	Serra La Nave.	1700	19.6	05/07/91	20 20
3	Mount Nocilla.	900	12.0	05/08/91	20 00
4	Schimmicci district.	390	6.2	06/08/91	23 00
5	Reitana district.	170	6.2	06/13/91	22 45
6	Ramondetta district.	350	12.0	06/10/91	22 45
7	S. Anna district.	20	24.0	06/15/91	22 30
8	Misterbianco.	200	5.0	07/13/91	20 45
9	Bottoga district.	200	12.6	07/03/91	21 15
10	Irmana district.	130	21.5	07/10/91	20 45
11	Gelso Bianco district.	20	9.4	07/14/91	20 45
12	Robavecchia district.	15	17.4	07/12/91	20 45
13	Catalicciardo district.	50	26.2	07/05/91	21 15

Table 2 - Intensity of the scattered radiation to the zenith along the direction Catania-Serra La Nave.

dist. (km)	I(erg cm^{-2} $s^{-1}$$ster^{-1}$ 10^{-7})	σ 10^{-7}
0.0	65573.19	1512.30
6.2	10069.62	164.04
12.0	4421.40	100.50
19.6	298.17	16.56

Table 3 - Intensity of the scattered radiation to the zenith along the direction Catania-Giarre

dist. (km)	I(erg cm^{-2} s^{-1} $ster^{-1}$ 10^{-7})	σ 10^{-7}
0.0	65573.19	1512.30
6.2	10828.65	199.68
12.0	3291.96	57.90
24.0	7022.13	218.88

Table 4 - Intensity of the scattered radiation to the zenith along the direction Catania-Paternò.

dist. (km)	I(erg cm^{-2} s^{-1} $ster^{-1}$ 10^{-7})	σ 10^{-7}
0.0	65573.19	1512.30
5.0	596290.02	3366.14
12.6	5912.98	225.81
21.5	2244.06	87.77

Table 5 - Intensity of the scattered radiation to the zenith along the direction Catania-Scordia.

dist. (km)	I(erg cm^{-2} s^{-1} $ster^{-1}$$10^{-7}$)	σ 10^{-7}
0.0	65573.19	1512.30
9.4	9288.99	414.74
17.4	4158.72	147.69
26.2	799.27	47.74

Table 6 - Serra La Nave, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	0.77	0.42
17.8	2.78	2.23
40.8	9.60	2.23
48.6	16.98	2.23
53.7	23.66	2.30
57.9	30.42	1.88
62.7	37.79	1.60

Table 7 - Mount Nocilla, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	7.10	2.01
4.8	10.52	1.54
10.4	17.29	2.21
17.0	22.65	1.54
21.2	30.28	1.94
25.6	36.38	1.94
32.8	51.59	2.01
37.8	64.32	2.55
42.9	72.76	3.08
47.4	87.10	11.46
52.3	117.58	10.85
56.4	148.87	10.25
61.1	183.31	10.12
64.5	216.21	10.99
68.5	251.58	11.06
70.8	286.69	10.72
76.5	318.38	8.11
80.4	352.82	11.52
90.0	380.29	6.03

Table 8 - Schimmicci district, scattered flux towards Catania.

Z	F(erg cm^{-2}s^{-1}10^{-9})	σ 10^{-9}
0.0	16.10	3.28
10.4	18.39	2.14
17.1	24.87	2.44
20.3	35.17	1.98
23.9	42.58	2.29
27.3	58.75	3.05
32.9	68.21	4.12
36.8	83.70	4.50
39.7	102.24	6.94
45.1	134.29	11.75
49.1	171.45	12.97
53.1	210.82	11.44
56.4	250.26	11.52
59.4	286.74	11.14
62.8	323.05	10.61
64.6	360.44	12.82
68.5	417.36	24.11
70.9	575.30	25.18
73.4	652.90	23.50
76.6	839.30	23.65

Table 9 - Reitana district, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	17.36	3.99
2.4	26.34	2.00
7.2	35.33	2.38
9.7	41.32	2.84
12.9	54.22	3.84
16.1	68.43	4.76
18.7	84.10	5.38
21.3	104.60	7.30
24.6	133.94	11.67
28.2	171.96	11.29
30.0	209.20	12.60
32.9	294.91	15.36
36.8	345.83	21.81
39.7	419.79	25.27
43.0	562.25	24.27
46.2	682.98	43.78
51.1	989.57	47.62
55.0	1254.45	57.22
57.9	1548.67	58.83
61.1	1843.20	52.99
66.4	2188.80	58.83

Table 10 - Ramondetta district, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	5.25	1.16
2.4	6.10	0.54
8.1	11.27	1.62
15.3	20.30	1.00
19.5	26.79	1.93
22.9	33.58	2.08
26.4	42.61	1.62
30.0	53.73	4.79
32.9	68.63	3.94
35.7	85.07	4.63
38.8	101.06	6.64
41.8	133.56	11.04
46.2	173.08	11.81
51.1	211.45	11.73
52.3	266.96	24.24
55.1	349.02	24.47
58.0	430.54	23.55
59.4	500.87	20.00
61.0	579.00	25.09
64.5	656.41	17.45

Table 11 - S. Anna district, scattered flux towards Catania.

Z	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	11.29	4.38
1.7	19.35	3.00
4.1	25.80	2.23
7.2	35.79	2.15
10.4	47.70	2.23
13.8	52.38	5.22
15.3	68.74	4.76
17.0	85.48	4.61
19.6	102.37	5.68
22.0	130.25	10.14
26.4	175.64	10.29
30.0	211.66	11.67
33.8	267.26	23.65
37.8	348.44	22.73
41.9	415.80	22.58
45.1	540.13	44.01
51.1	693.27	46.77
55.0	849.18	45.24
57.9	998.55	49.77
62.8	1182.95	65.28
64.5	1402.52	73.42
68.6	1651.43	87.32
73.4	1876.84	60.13

Table 12 - Misterbianco, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	949.12	76.91
9.7	982.66	45.99
23.0	1356.10	68.07
30.0	1753.23	47.22
36.8	2117.88	52.26
41.8	2495.07	53.33
45.1	2888.38	66.77
49.8	3241.80	73.50
52.3	3646.11	75.86
57.9	4234.70	128.50
64.6	4994.42	116.82
70.8	5702.80	225.53
73.5	6497.06	245.94
76.6	7242.18	168.77
80.4	7954.16	218.28

Table 13 - Bottoga district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	9.96	4.63
0.8	12.04	1.78
3.2	19.92	2.78
6.4	26.32	2.01
11.2	34.89	2.62
12.8	42.00	1.93
16.1	57.44	4.79
18.7	66.39	5.02
21.2	87.39	3.71
25.5	101.90	7.57
30.0	135.87	9.88
34.8	174.70	12.12
38.8	212.84	12.04
44.1	268.04	24.55
48.7	343.62	23.31
53.8	425.53	23.78
57.9	503.19	21.85
61.0	611.96	48.33
66.4	780.80	42.77
70.9	922.15	51.80
73.4	1030.34	47.79
76.5	1247.01	59.06

Table 14 - Irmana district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	3.72	1.78
9.7	4.18	1.47
23.9	12.46	1.78
31.0	18.89	2.48
34.8	27.01	2.24
39.8	35.06	2.55
43.0	41.95	1.86
47.4	53.72	4.33
51.1	70.05	5.34
53.8	84.75	4.02
58.0	103.95	7.12
62.8	134.99	12.00
68.5	173.76	10.84
73.4	214.24	13.47
76.5	269.74	20.90
80.5	327.32	15.56

Table 15 - Gelso Bianco district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	14.84	8.30
1.6	17.96	2.66
4.9	24.73	1.75
6.4	36.83	0.53
8.0	42.46	1.98
10.5	54.18	4.57
13.7	66.13	3.80
15.4	92.92	4.41
18.7	134.62	8.45
23.0	186.67	24.12
27.3	265.59	25.80
31.0	339.79	20.70
33.7	416.04	25.11
37.8	524.48	43.22
41.9	683.07	47.03
45.2	851.79	51.44
48.7	1041.35	62.71
51.1	1258.54	71.53
55.0	1503.51	73.13
57.9	1743.91	94.82
62.8	2071.14	109.66
67.6	2632.83	239.87
73.4	3437.58	224.27

Table 16 - Robavecchia district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	6.84	3.00
2.4	11.21	1.84
5.7	19.58	2.15
10.4	25.57	2.46
12.9	34.48	2.30
15.4	40.63	1.77
17.9	53.07	4.30
21.2	68.89	6.14
23.9	84.10	3.99
26.4	103.53	7.22
30.0	133.94	11.06
32.9	172.80	12.75
36.7	209.82	10.91
39.7	267.19	24.42
44.1	344.52	22.66
46.2	420.71	23.27
51.1	532.15	46.77
55.0	687.67	47.69
59.4	862.00	58.14
62.8	1057.84	61.36
66.4	1258.06	68.43
70.9	1457.82	59.90

Table 17 - Catalicciardo district, scattered flux towards Catania.

Z°	F(erg cm^{-2} s^{-1} 10^{-9})	σ 10^{-9}
0.0	1.61	1.07
8.0	3.21	1.84
24.6	10.63	1.38
35.8	17.90	1.61
41.8	27.46	1.53
45.1	34.20	2.22
48.7	41.77	2.45
55.0	55.84	2.30
59.4	68.24	4.67
62.8	82.77	4.13
66.4	103.58	7.42
70.9	132.42	11.40
76.5	169.29	13.08
80.4	209.69	10.02

Table 18 - Scattered flux from 2π ster along the direction Catania-Scordia.

dist.	F(erg cm^{-2} s^{-1} 10^{-7})	σ 10^{-7}
0.0	968.01	3.04
9.4	65.07	0.57
17.4	16.13	0.18
26.2	3.21	0.02