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Stellar multiplicities and signatures of supernova-induced star formation in the Eta Carinæ nebula

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Abstract. It is found that in the Eta Carinæ nebula, the single, binary, triple and quadruple stellar systems follow a proportion of 52 : 35 : 11 : 2, which is quite similar to that obtained by Duquennoy (1988) for the field stars, with the proportion 51 : 39 : 8 : 2. The multiple stellar systems in the Eta Carinæ nebula are often found to form arches, most of which, on the basis of a number of statistical analyses, might be regarded as physical associations rather than chance alignments of the foreground stars. If this inference is correct, these reported stellar arcs in the Eta Carinæ nebula might have borne the direct signatures of possible supernova-induced star formation. The total number of arcs studied is 96 within an area of the region covering about 0.67 square degree, divided into six square-shaped regions, based on a 0.51 m × 0.76 m sized photograph taken with the 3.9 m Anglo-Australian Telescope in 1978.

Key words : Eta Carinæ nebula—stellar multiplicities—supernova-induced star formation

1. Introduction

The Eta Carinæ nebula, though being one of the most prominent nebulæ in the sky, has strangely enough not received the due attention of the astronomers. Feinstein *et al.* (1973) have cataloged the brightest members of the nebula with the distance moduli given separately for many stars in it. For the present purpose of the work, we have used the poster-sized (20 × 30″) photograph issued by the Anglo-Australian Telescope Board in 1978 and taken with the 3.8 m Anglo-Australian Telescope. We have adopted a distance of 1.84 kpc to the nebula as notified on the backside of the poster, and an average distance modulus of $(V_0 - M_V) \geq 12^m.5$ from the tables in Feinstein *et al.* (1973).

The purpose of the present study has been to determine the stellar multiplicity ratios in physically apparent multiple stellar systems in the nebula and to quantify as many arches as

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possible that have 3 or more stellar components. To the best of our knowledge, such an investigation has not been carried out by anybody else, in particular for the Eta Carinæ nebula, which is very active from the point of view of massive star formation.

2. Method of study

The actual photograph on a reduced scale is shown in figure 1 with the boundaries of the six square-shaped regions marked with numbers I to VI. The individual arches formed by close association of stars are marked with numbers 1, 2, ..., etc. in the grids designated by 'Bb' etc., as marked in the six panel regions, namely, I to VI, in figure 2. The coordinates of the members of each arc in a grid are determined by tracing them on a transparent graph sheet, and a small numerical routine has been used to determine the approximate radii of these arcs along with their best possible location of centres. The visual limit of resolution for reading the coordinates corresponds to about 80,000 AU (= 0.08 pc) in situ. Table 1 displays these data, the various entries in different columns being explained in the footnotes following the table. The radius of an arc consisting of 3 or more stars is expressed in units of pc in the 11th column of table 1.

For the determination of the absolute visual magnitudes of the component stars in the table, we compared the star's brightness with the reported visual magnitude of its nearest bright star included in the sample of Feinstein *et al.* (1973). Since we did not use a photo densitometer, our estimates can go wrong by about $0^{m}.5$, and therefore, a rounded figure for M_V appears in the 12th column of table 1.

In the 13th and 14th columns of table 1, we have given rough estimates of the mass (m) of individual stars based on the $m - M_V$ relation assuming respectively the single-star and systemic mass-luminosity calibrations from Basu & Rana (1992). The total mass in individual arcs are correspondingly presented in the 15th and 16th columns of table 1. In order to clarify the use of two different calibrations, it should be noted that stars in Eta Carinæ nebula, which appear as a single star from a great distance might themselves be having unresolvable binary or multiple components (like, for example, those of the nearby field stars), in which case the $m - M_V$ relation to be used will be different. Following Basu & Rana (1992), the actual calibrations for $m - M_V$ relation for the assumed cases of single stars and unresolvable multiple stars with the mass of the primary component as well as of the system are given in table 2. Further in the above mentioned work, the mass ratio (q) for idealised binaries are assumed to be 0.25 for the primary mass component $m_p \leq 1.0$ (all masses being expressed in units of $M_\odot$), $q = 1.0$ for $m_p \geq 10.0$ and $q = 0.25 + 0.75 \log m$ for $1.0 < m < 10$. Thus, the two different mass estimates appearing in the 13th and 14th columns are referring to the second possible case, namely, that of accounting for the unseen multiple components. Also the error in the magnitude estimates allow for error in mass of each star. Consequently, the 15th and 16th columns correspond to the mass of both the detectable and the unresolvable component stars in a given arch with magnitude of error bars being tabulated in the respective following rows of these two columns.

In order to determine the ratios of the single, binary, triple and quadruple stellar systems in the entire photograph (dropping ofcourse, the unambiguous foreground stars), we counted only the apparently identifiable systems supposedly belonging to the nebula itself. In the six regions, a total of 507 single stars, 333 binaries, 98 triple stars and 18 quadruples are found. Table 3 gives the break up of all these counts for individual regions, namely, I to VI.

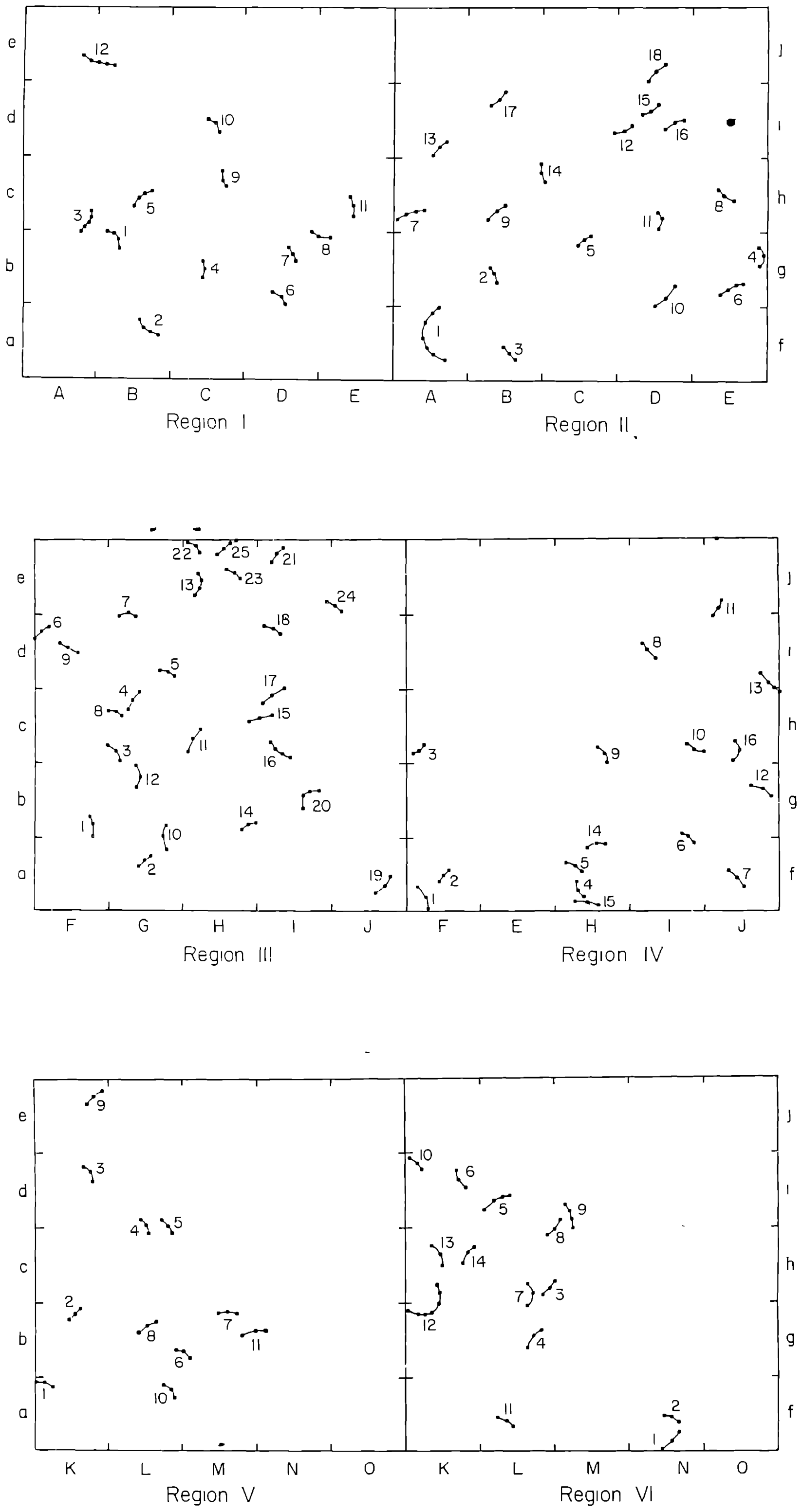

Figure 2. A total of 96 arcs are shown in the six regions referred to in figure 1.

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Table 1. Data for the individual stellar arcs

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
I	1	Bb	4	(1)	6.6	8.8	5.20	8.83	52	0.58	–2.5	9.3	(15.3)	20	(31)
				(2)	6.5	9.3			2.8		–1.5	6.3	(9.9)	±4	±6
				(3)	6.3	9.7			2.1		1.5	2.2	(3.2)		
				(4)	5.8	10.1					2.5	1.7	(2.2)		
	*2	Ba	4	(1)	9.3	3.3	9.62	4.75	.38	0.61	–0.5	4.3	(7.0)	11	(17)
				(2)	9.0	3.4			3.8		1.5	2.2	(3.2)	±2	±4
				(3)	8.6	3.7			2.7		2.5	1.7	(2.2)		
				(4)	8.4	3.9				0.5	3.0	(4.6)			
	3	Ac	5	(1)	3.6	9.9	1.49	12.18	41	1.26	1.5	2.2	(3.2)	16	(25)
				(2)	3.8	10.2			3.6		0.5	3.0	(4.6)	±3	±4
				(3)	4.0	10.6			2.5		0.5	3.0	(4.6)		
				(4)	4.2	10.8					0.0	3.5	(5.4)		
				(5)	4.4	11.3					–0.5	4.3	(7.0)		
	4	Cb	3	(1)	12.7	7.4	12.00	7.80	.42	0.34	–0.5	4.3	(7.0)	12	(19)
				(2)	12.8	7.9			3.5		–0.5	4.3	(7.0)	±2	±3
				(3)	12.7	8.2			2.5		0.0	3.5	(5.4)		
	*5	Bc	4	(1)	7.5	11.8	8.69	10.63	.44	0.70	3.5	1.3	(1.7)	9	(13)
				(2)	7.9	12.1			3.3		–0.5	4.3	(7.0)	±1	±2
				(3)	8.3	12.2			2.4		1.5	2.2	(3.2)		
				(4)	8.7	12.3					3.5	1.3	(1.7)		
	6	Db	3	(1)	17.8	5.3	17.10	5.00	.54	0.23	3.5	1.3	(1.7)	6	(8)
				(2)	17.0	5.7			2.7		0.5	3.0	(4.6)	±1	±2
				(3)	17.1	5.9			2.0		3.5	1.3	(1.7)		
	7	Db	3	(1)	18.5	7.6	15.50	6.35	49	1.35	0.5	3.0	(4.6)	14	(21)
				(2)	18.3	8.0			3.0		–0.5	4.3	(7.0)	±2	±3
				(3)	18.1	8.3			2.2		–1.5	6.3	(9.9)		
	8	Eb	3	(1)	19.4	10.1	21.60	12.75	.77	1.42	1.5	2.2	(3.2)	13	(20)
				(2)	20.0	9.7			1.9		–0.5	4.3	(7.0)	±2	±3
				(3)	20.8	9.4			1.3		–1.5	6.3	(9.9)		
	9	Cc	3	(1)	13.5	14.9	19.10	16.85	50	2.46	2.5	1.7	(2.2)	8	(12)
				(2)	13.7	14.4			2.9		1.5	2.2	(3.2)	±1	±2
				(3)	13.9	14.0			2.1		–0.5	4.3	(7.0)		
	10	Cd	3	(1)	12.6	17.6	11.79	16.67	.61	0.72	0.5	3.0	(4.6)	9	(15)
				(2)	13.1	17.2			2.4		–0.5	4.4	(7.0)	±1	±2
				(3)	13.4	16.7			1.8		1.5	2.2	(3.2)		
	*11	Ec	3	(1)	22.4	11.0	15.35	14.15	.70	3.04	1.5	2.2	(3.2)	8	(12)
				(2)	22.5	11.6			2.1		0.0	3.5	(5.4)	±1	±2
				(3)	22.6	12.4			1.5		1.5	2.2	(3.2)		

(*Continued*)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
I	12	Ae	5	(1)	4 4	21 8	6.18	23 38	47	0 98	2.5	1.7	(2 2)	19	(30)
		Be		(2)	4 6	21.6			3.1		0.5	3 0	(4.6)	±4	±6
				(3)	4.9	21.3			2.3		–0.5	4 3	(7.0)		
				(4)	5.5	21 1					–2 0	7.6	(12.0)		
				(5)	6 1	21 0					0 5	3.0	(4 6)		
II	*1	Af	7	(1)	3 6	26 5	3.85	28 25	73	0.73	–1.0	5 1	(8.0)	26	(41)
				(2)	2.6	27.0			2.0		–1.0	5.1	(8.0)	±6	±9
				(3)	2 3	27 4			1.4		0.5	3.0	(4.6)		
				(4)	2 1	28.1					0.5	3.0	(4 6)		
				(5)	2 3	29 1					0.5	3.0	(4.6)		
				(6)	3 6	29.9					–0.5	4.3	(7.0)		
				(7)	3 9	30.0					0 5	3.0	(4 6)		
	2	Bg	3	(1)	6 7	32 6	5 86	31.82	49	0.48	–1.5	6 3	(9.9)	10	(15)
				(2)	6 9	32 3			3 0		0.5	3 0	(4.6)	±1	±2
				(3)	7.0	31 7			2 2		2 5	1.7	(2 2)		
	3	Bf	3	(1)	7 7	26.4	6.25	24 05	.39	1.14	–1 0	5 1	(8 0)	12	(17)
				(2)	8 1	26 1			3 7		–0.5	4 3	(7 0)	±2	±3
				(3)	8.3	25 9			2.6		1.5	2.2	(3 2)		
	4	Eg	3	(1)	24 8	33.4	24 26	33 60	.32	0.26	0.5	3.0	(4.6)	7	(10)
				(2)	24.9	33.7			4 6		1.5	2 2	(3 2)	±1	±2
				(3)	24.8	34 0			3.1		2.5	1 7	(2.2)		
	5	Cg	4	(1)	12 9	24.3	14 30	22 85	.28	0.84	–0 5	4.3	(7.0)	14	(20)
				(2)	13.1	24.5			5.2		0.5	3.0	(4.6)	±2	±4
				(3)	13 3	24.6			3.3		–0.5	4.3	(7.0)		
				(4)	13 5	24.7					1 5	2.2	(3.2)		
	6	Eg	4	(1)	22.7	31.0	23.41	30.37	.44	0.39	–1.5	6 3	(9.9)	11	(17)
				(2)	23 0	31 2			3.3		0 5	3.0	(4.6)	±2	±3
				(3)	23.3	31.3			2.4		2.5	1.7	(2.2)		
				(4)	23.6	31 3					3 5	1 3	(1.7)		
	7	Ah	4	(1)	0.3	36.9	1.81	32 78	81	1.44	–0 5	4.3	(7.0)	14	(20)
				(2)	0.9	36 2			1.8		–0.5	4 3	(7.0)	±2	±4
				(3)	1.5	36.3			1.2		0.5	3 0	(4 6)		
				(4)	2 5	36.4					1 5	2.2	(3 2)		
	8	Eh	3	(1)	21 8	38.1	23.36	38 48	.44	0 67	–1 0	5.1	(7 8)	14	(22)
				(2)	21 9	37.7			3.3		–0.5	4 3	(7.0)	±2	±4
				(3)	22 3	37 3			2.4		–0 5	4.3	(7.0)		
	*9	Bh	3	(1)	6.4	35.9	3.65	39 00	73	1 73	2.5	1.7	(2 2)	9	(15)
				(2)	6.8	36.3			2.0		0.5	3.0	(4.6)	±1	±2
				(3)	7.4	37.2			1.4		–0.5	4 3	(7 0)		

(*Continued*)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
II	10	Dg	3	(1)	17.3	30.2	16.40	33.00	.66	1.22	0.5	3.0	(4.6)	9	(15)
				(2)	18.1	30.6			2.2		0.0	3.5	(5.4)	±1	±2
				(3)	18.8	31.3			1.6		0.5	3.0	(4.6)		
	11	Dh	3	(1)	17.9	35.2	17.47	35.70	.56	0.29	−1.5	6.3	(9.9)	16	(25)
				(2)	18.2	35.9			2.6		−1.0	5.1	(8.0)	±3	±5
				(3)	18.2	36.2			1.9		−0.5	4.3	(7.0)		
	12	Ci	3	(1)	14.9	41.5	14.71	42.91	.46	0.59	−0.5	4.3	(7.0)	9	(15)
		Di		(2)	15.3	41.6			3.2		0.5	3.0	(4.6)	±1	±2
				(3)	15.7	41.9			2.3		1.5	2.2	(3.2)		
	13	Ai	3	(1)	2.3	40.0	4.22	38.67	.97	0.96	0.5	3.0	(4.6)	15	(24)
				(2)	2.8	40.5			1.5		−0.5	4.3	(7.0)	±2	±4
				(3)	3.9	41.0			0.8		−2.0	7.6	(12.0)		
	14	Ch	3	(1)	10.2	38.7	11.81	39.23	.70	0.71	1.5	2.2	(3.2)	7	(11)
				(2)	10.1	39.2			2.9		1.5	2.2	(3.2)	±1	±2
				(3)	10.2	39.7			2.1		0.5	3.0	(4.6)		
	15	Di	3	(1)	16.2	43.1	15.57	44.02	.25	0.47	−0.5	4.3	(7.0)	8	(13)
				(2)	16.4	43.2			5.8		1.5	2.2	(3.2)	±1	±2
				(3)	16.6	43.4			3.5		1.5	2.2	(3.2)		
	16	Di	3	(1)	17.6	42.7	18.93	41.92	.58	0.64	−0.5	4.3	(7.0)	9	(15)
				(2)	18.2	43.3			2.5		0.5	3.0	(4.6)	±1	±2
				(3)	18.5	43.4			1.8		1.5	2.2	(3.2)		
	17	Bi	3	(1)	6.6	42.9	4.68	45.77	.42	1.42	0.5	3.0	(4.6)	9	(15)
				(2)	7.0	43.3			3.5		−0.5	4.3	(7.0)	±1	±2
				(3)	7.2	43.5			2.5		2.5	1.7	(2.2)		
	18	Dj	4	(1)	16.9	44.7	19.62	44.02	.49	1.16	−1.0	5.1	(8.0)	18	(29)
				(2)	17.2	45.4			3.0		−0.5	4.3	(7.0)	±3	±5
				(3)	17.5	45.8			2.2		−0.5	4.3	(7.0)		
				(4)	17.7	46.3					−0.5	4.3	(7.0)		
III	1	Fb	3	(1)	29.0	4.9	70.58	8.43	.73	17.28	−2.0	7.6	(12.0)	17	(27)
				(2)	29.0	5.6			2.0		−1.0	5.1	(8.0)	±3	±5
				(3)	28.9	6.4			1.4		−0.5	4.3	(7.0)		
	2	Ga	3	(1)	31.7	2.8	42.97	−14.9	.36	8.69	−1.5	6.3	(9.9)	15	(22)
				(2)	32.1	3.0			4.1		−1.0	5.1	(8.0)	±3	±5
				(3)	32.3	3.2			2.8		0.0	3.5	(5.4)		
	3	Gc	3	(1)	30.9	10.2	29.35	9.90	.47	0.63	−0.5	4.3	(7.0)	9	(15)
				(2)	30.7	10.6			3.1		0.5	3.0	(4.6)	±1	±2
				(3)	30.4	11.0			2.3		2.5	1.7	(2.2)		
	*4	Gc	3	(1)	31.7	13.6	48.80	11.00	.50	7.18	2.5	1.7	(2.2)	13	(19)
				(2)	31.8	14.2			2.9		0.0	3.5	(5.4)	±2	±4
				(3)	31.9	14.7			2.1		−2.0	7.6	(12.0)		

(Continued)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
III	5	Gd	3	(1)	34.3	16.1	33.48	15.01	63	0.54	2.5	1.7	(2.2)	8	(12)
				(2)	33.6	16.3			2.3		0.5	3.0	(4.6)	±1	±2
				(3)	33.1	16.3			1.7		0.0	3.5	(5.4)		
	6	Fd	3	(1)	25.2	18.4	26.22	17.65	42	0.54	–2.5	9.3	(15.3)	14	(22)
				(2)	25.6	18.8			3.5		0.5	3.0	(4.6)	±2	±3
				(3)	26.4	19.0			2.5		2.5	1.7	(2.2)		
	7	Gd	3	(1)	30.4	19.9	31.30	18.84	.49	0.54	2.5	1.7	(2.2)	9	(15)
		Ge		(2)	30.8	20.1			3.0		–0.5	4.3	(7.0)	±1	±2
				(3)	31.3	20.0			2.2		0.5	3.0	(4.6)		
	8	Gc	3	(1)	30.8	13.5	30.35	13.21	43	0.20	0.5	3.0	(4.6)	7	(10)
				(2)	30.4	13.7			3.4		1.5	2.2	(3.2)	±1	±2
				(3)	30.0	13.6			2.4		2.5	1.7	(2.2)		
	9	Fd	3	(1)	27.5	17.5	27.50	18.75	56	0.52	–1.5	6.3	(9.9)	12	(19)
				(2)	26.7	17.8			2.6		0.0	3.5	(5.4)	±2	±3
				(3)	26.5	18.0			1.9		1.5	2.2	(3.2)		
	10	Ga	3	(1)	34.2	4.0	35.62	4.87	.49	0.72	–0.5	4.3	(7.0)	9	(15)
				(2)	34.0	4.4			3.0		0.5	3.0	(4.6)	±1	±2
				(3)	33.9	5.1			2.2		1.5	2.2	(3.2)		
	11	Hc	3	(1)	35.5	10.9	44.22	8.28	.59	3.79	–2.0	7.6	(12.0)	15	(24)
				(2)	35.8	11.8			1.7		–0.5	4.3	(7.0)	±2	±3
				(3)	36.2	12.6			1.1		0.5	3.0	(8.0)		
	12	Gb	3	(1)	31.8	8.6	30.34	9.35	77	0.67	0.5	3.0	(4.6)	12	(20)
				(2)	32.0	9.2			1.9		–0.5	4.3	(7.0)	±2	±3
				(3)	31.9	10.0			1.3		–1.0	5.1	(8.0)		
	13	He	4	(1)	35.1	21.2	34.35	22.10	.61	0.48	–1.0	5.1	(8.0)	17	(26)
				(2)	35.5	21.7			2.4		–0.5	4.3	(7.0)	±3	±5
				(3)	35.5	22.1			1.8		–0.5	4.3	(7.0)		
				(4)	35.3	22.9					0.5	3.0	(4.6)		
	14	Hb	3	(1)	39.3	6.1	40.02	5.11	35	0.52	–1.0	5.1	(8.0)	16	(25)
				(2)	39.5	6.3			4.2		–1.5	6.3	(9.9)	±3	±5
				(3)	39.9	6.4			2.9		0.5	4.3	(7.0)		
	15	Hc	3	(1)	39.8	12.8	40.66	11.41	.42	0.66	0.5	3.0	(4.6)	17	(28)
		Ic		(2)	40.1	12.9			3.5		–1.0	5.1	(8.0)	±3	±5
				(3)	40.6	13.0			2.5		–2.5	9.3	(15.3)		
	16	Ic	4	(1)	41.8	10.4	43.85	12.85	61	1.35	3.5	1.3	(1.7)	9	(14)
				(2)	41.4	10.8			2.4		1.5	2.2	(3.2)	±1	±2
				(3)	41.0	11.4			1.8		0.5	3.0	(4.6)		
				(4)	40.8	11.9					0.5	3.0	(4.6)		
	17	Ic	3	(1)	40.4	14.2	42.94	12.56	.91	1.24	1.5	2.2	(3.2)	9	(15)
		Id		(2)	41.0	14.8			1.6		–0.5	4.3	(7.0)	±1	±2
				(3)	41.9	15.4			1.0		0.5	3.0	(4.6)		

(*Continued*)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
III	18	Id	3	(1)	41 9	19.0	40.80	16.42	.42	1.16	0 0	3 5	(5 4)	10	(16)
				(2)	41.4	19 2			3.5		1.5	2.2	(3.2)	±1	±2
				(3)	40.7	19.2			2.5		–0 5	4 3	(7.0)		
	*19	Ja	3	(1)	48.2	0 9	47.88	2.01	.56	0 49	–1 0	5 1	(8.0)	22	(35)
				(2)	48 7	1 1			2.6		–2.5	9.3	(15.3)	±4	±6
				(3)	49.0	1 6			1 9		–2.0	7.6	(12.0)		
	20	Ib	4	(1)	43.3	7.8	43.70	7.90	.33	0 19	1 5	2.2	(3.2)	14	(23)
				(2)	43 4	8 2			4 4		–0.5	4.3	(7.0)	±2	±4
				(3)	43.7	8 4			3.0		0.0	3 5	(5.4)		
				(4)	44 0	8.3					–0 5	3.5	(5 4)		
	21	Ie	3	(1)	41.0	24.0	41.75	24.08	.35	0.32	–2 5	9.3	(15.3)	17	(28)
				(2)	41.0	24.2			4.2		–1 0	5.1	(8 0)	±3	±5
				(3)	41.3	24.7			2 9		0 5	3 0	(4 6)		
	22	He	3	(1)	36.4	24.4	34.73	22.86	.39	0.93	–3 5	14.5	(23 5)	29	(47)
				(2)	36.0	24 7			3.7		–2.5	9.3	(15 3)	±6	±9
				(3)	35.8	24.9			2.6		–1 0	5 1	(8 0)		
	23	He	3	(1)	38.0	23.6	38.07	22 46	36	0 45	–0.5	4 3	(7.0)	9	(14)
				(2)	38.4	23 5			4 1		0.5	3.0	(4 6)	±1	±2
				(3)	38.7	23.6			2.8		2 5	1.7	(2 2)		
	24	Je	3	(1)	45 5	20.3	43.92	19.67	42	0.67	–1 5	6 3	(9.9)	14	(21)
				(2)	45.3	20.6			3 5		–0 5	4.3	(7.0)	±2	±3
				(3)	45.0	20.9			2.5		0.5	3.0	(4.6)		
	*25	He	6	(1)	37 5	24.1	38.80	23.75	46	0 56	–0.5	4.3	(7.0)	49	(80)
				(2)	37.6	24.3			3 2		0 0	3.5	(5.4)	±11	±19
				(3)	37.7	24.5			2.3		–2 5	9.3	(15.3)		
				(4)	37.9	24.8					1 5	2.2	(3 2)		
				(5)	38 1	25.2					–5 0	18.7	(30.6)		
				(6)	38 6	25 6					–3 0	11.5	(19 0)		
IV	1	Ff	3	(1)	26.6	24 8	20.04	21.35	.49	3.04	–2 5	9.3	(15 3)	20	(32)
				(2)	26.2	25.4			3.0		–1.5	6.3	(9 3)	±4	±6
				(3)	25.6	26.2			2.2		–0.5	4.3	(7.0)		
	2	Ff	3	(1)	27.2	26 8	27.96	26 96	.46	0.34	–0 5	4 3	(7.0)	11	(17)
				(2)	27 3	27.3			3.2		0 0	3.5	(5.4)	±2	±3
				(3)	27.6	27.6			2 3		0.5	3 0	(4 6)		
	3	Fh	3	(1)	25.5	35.5	25.18	36 02	.22	0.26	0.5	3.0	(4.6)	7	(10)
				(2)	25 7	35.6			6.6		1.5	2.2	(3.2)	±1	±2
				(3)	25 8	35.8			3.8		2.5	1.7	(2.2)		
	4	Hf	3	(1)	35.9	26.3	40.43	28.23	.27	2.06	–0.5	4.3	(7 0)	10	(16)
				(2)	35.8	26.5			5.4		0.0	3.5	(5.4)	±2	±3
				(3)	35.7	26.8			3 4		1.5	2 2	(3.2)		

(*Continued*)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
IV	5	Hf	4	(1)	36.7	27.4	35.54	26.62	.49	0.55	−1.5	8.1	(12.6)	10	(16)
				(2)	36.3	27.7			3.0		3.5	1.3	(1.7)	±2	±3
				(3)	35.9	27.9			2.2		4.5	1.1	(1.4)		
				(4)	35.6	28.0					6.5	0.6	(0.7)		
	6	If	3	(1)	44.0	29.8	42.72	29.31	.25	0.55	−2.5	9.3	(15.3)	21	(33)
				(2)	43.9	30.0			5.8		−1.5	6.3	(9.9)	±4	±6
				(3)	43.7	30.2			3.5		−1.0	5.1	(8.0)		
	7	Jf	3	(1)	47.5	26.8	45.02	24.42	.70	1.41	−1.0	5.1	(8.0)	8	(13)
				(2)	47.1	27.2			2.1		2.5	1.7	(2.2)	±2	±3
				(3)	46.4	27.6			1.5		3.5	1.3	(1.7)		
	8	Ii	3	(1)	41.6	42.6	48.78	50.13	.56	4.32	−3.5	14.5	(23.5)	28	(46)
				(2)	41.3	42.9			2.6		−2.0	7.6	(12.0)	±6	±9
				(3)	40.8	43.4			1.9		−1.5	6.3	(9.9)		
	9	Hh	3	(1)	38.8	35.0	36.74	34.67	.49	0.89	−1.5	6.3	(9.9)	10	(16)
				(2)	44.5	35.9			2.6		0.0	3.5	(5.4)	±3	±5
				(3)	44.0	36.2			1.9		−1.5	6.3	(9.9)		
	*10	Ih	3	(1)	45.0	35.7	45.49	38.06	.56	1.00	−1.5	6.3	(9.9)	16	(25)
				(2)	44.5	35.9			2.6		0.0	3.5	(5.4)	±3	±5
				(3)	44.0	36.2			1.9		−1.5	6.3	(9.9)		
	11	Ji	3	(1)	45.9	44.8	44.53	45.52	.32	0.63	−3.0	11.5	(19.0)	16	(25)
		Jj		(2)	46.0	45.1			4.6		0.5	3.0	(4.6)	±3	±5
				(3)	46.1	45.4			3.1		3.5	1.3	(1.7)		
	*12	Jg	3	(1)	49.4	34.6	48.00	32.55	.54	1.59	−3.5	14.5	(23.5)	30	(49)
				(2)	48.8	34.9			2.7		−1.5	6.3	(9.9)	±6	±10
				(3)	48.4	35.0			2.0		−2.5	9.3	(15.3)		
	13	Ji	4	(1)	50.4	39.7	54.89	44.50	.61	2.88	−3.5	14.5	(23.5)	28	(45)
		Ki		(2)	50.0	40.0			2.4		−1.5	6.3	(9.9)	±6	±9
				(3)	49.8	40.3			1.8		0.5	3.0	(4.6)		
				(4)	49.2	41.0					−0.5	4.3	(7.0)		
	14	Hf	3	(1)	37.6	29.2	36.34	33.12	.43	1.73	−2.0	7.6	(12.0)	18	(28)
				(2)	38.0	29.3			3.4		−0.5	4.3	(7.0)	±3	±5
				(3)	38.4	29.5			2.4		−1.5	6.3	(9.9)		
	15	Hf	4	(1)	46.4	25.8	46.90	24.23	.34	0.68	−1.5	6.3	(9.9)	19	(29)
				(2)	46.6	25.9			4.3		0.5	3.0	(4.6)	±4	±6
				(3)	47.2	25.9			2.9		−0.5	4.3	(7.0)		
				(4)	47.4	25.8					−1.5	6.3	(9.9)		
	16	Ja	3	(1)	47.3	35.3	45.47	35.68	.39	0.76	−2.5	9.3	(15.3)	20	(32)
				(2)	47.3	35.7			3.7		−1.5	6.6	(9.9)	±4	±6
				(3)	47.3	36.1			2.6		−0.5	4.3	(7.0)		

(*Continued*)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
V	1	Ka	3	(1)	50.0	4.8	49.92	3.95	27	0.33	1.5	2.2	(3.2)	4	(6)
				(2)	50.2	4.7			5.4		4.5	1.1	(1.4)	±1	±1
				(3)	50.5	4.6			3.4		4.5	1.1	(1.4)		
	2	Kb	3	(1)	52.3	8.9	51.73	9.62	.38	0.38	0.5	3.0	(4.6)	9	(14)
				(2)	52.5	9.1			3.8		0.5	3.0	(4.6)	±2	±3
				(3)	52.7	9.5			2.7		0.5	3.0	(4.6)		
	3	Kd	3	(1)	53.8	17.6	53.18	17.85	.43	0.26	0.5	3.0	(4.6)	11	(17)
				(2)	53.8	18.1			3.4		0.0	3.5	(5.4)	±2	±3
				(3)	53.6	18.4			2.4		−0.5	4.3	(7.0)		
	4	Lc	3	(1)	57.7	15.1	56.45	14.50	32	0.55	−0.5	4.3	(7.0)	11	(18)
				(2)	57.5	15.3			4.6		−0.5	4.3	(7.0)	±2	±3
				(3)	57.3	15.6			3.1		0.5	3.0	(4.6)		
	5	Lc	3	(1)	58.4	14.9	57.47	14.50	.30	0.40	−2.0	9.4	(14.9)	17	(26)
				(2)	58.3	15.2			4.9		−0.5	4.3	(7.0)	±3	±5
				(3)	58.1	15.4			3.2		0.5	3.0	(4.6)		
	6	Lb	3	(1)	60.5	6.0	59.87	5.92	.46	0.24	0.5	3.0	(4.6)	8	(11)
		Mb		(2)	60.2	6.4			3.2		0.5	3.0	(4.6)	±1	±2
				(3)	59.8	6.5			2.3		2.5	1.7	(2.2)		
	7	Mb	3	(1)	62.4	9.1	63.37	5.87	50	1.40	2.5	1.7	(2.2)	9	(14)
				(2)	62.8	9.2			2.9		−0.5	4.3	(7.0)	±2	±3
				(3)	63.2	9.3			2.1		0.5	3.0	(4.6)		
	8	Lb	3	(1)	67.1	7.3	67.88	6.98	46	0.34	1.5	2.2	(3.2)	12	(18)
				(2)	67.4	7.7			3.2		−1.5	6.3	(9.9)	±2	±3
				(3)	67.8	7.8			2.3		−0.5	4.3	(7.0)		
	9	Ke	3	(1)	53.4	23.5	56.33	21.27	.54	1.54	−1.5	6.3	(9.9)	13	(20)
				(2)	53.8	24.0			2.7		−0.5	3.0	(4.6)	±2	±4
				(3)	54.1	24.3			2.0		1.5	2.2	(3.2)		
	10	La	3	(1)	59.4	3.5	57.93	3.48	.49	0.59	−0.5	4.3	(7.0)	11	(18)
				(2)	59.3	4.0			3.0		−0.5	4.3	(7.0)	±2	±3
				(3)	59.1	4.4			2.2		0.5	3.0	(4.6)		
	11	Mb	3	(1)	64.1	7.8	64.83	7.29	.63	0.37	−1.0	5.1	(8.0)	12	(20)
		Nb		(2)	64.6	8.2			2.3		−0.5	4.3	(7.0)	±2	±4
				(3)	65.2	8.1			1.7		0.5	3.0	(4.6)		
VI	1	Nf	3	(1)	67.6	25.1	56.77	28.97	47	4.75	2.5	1.7	(2.2)	9	(15)
				(2)	67.8	25.7			3.1		0.5	3.0	(4.6)	±2	±3
				(3)	67.9	26.0			2.3		−0.5	4.3	(7.0)		
	2	Nf	3	(1)	68.3	27.1	67.80	27.00	.27	0.19	0.5	3.0	(4.6)	7	(10)
				(2)	68.2	27.4			5.4		1.5	2.2	(3.2)	±1	±2
				(3)	68.0	27.5			3.4		2.5	1.7	(2.2)		

(Continued)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
VI	3	Lh	3	(1)	59.4	35.8	59.26	36.25	43	0.21	1.5	2.2	(3.2)	13	(20)
				(2)	59.7	36.0			3.4		−0.5	4.3	(7.0)	±2	±4
				(3)	59.7	36.5			2.4		−1.5	6.3	(9.9)		
	4	Lg	3	(1)	58.1	31.9	60.18	31.68	.37	0.88	2.5	1.7	(2.2)	7	(10)
				(2)	58.2	32.4			3.9		1.5	2.2	(3.2)	±1	±2
				(3)	58.3	32.6			2.7		0.5	3.0	(4.6)		
	*5	Li	4	(1)	55.4	41.2	56.75	39.98	54	0.76	2.5	1.7	(2.2)	12	(18)
				(2)	55.7	41.5			2.7		0.5	3.0	(4.6)	±2	±4
				(3)	56.3	41.8			2.0		−0.5	4.3	(7.0)		
				(4)	57.0	41.8					0.5	3.0	(4.6)		
	6	Ki	3	(1)	54.2	42.7	55.92	44.65	.61	1.09	−1.0	5.1	(8.0)	10	(16)
				(2)	53.8	43.2			2.4		0.5	3.0	(4.6)	±2	±3
				(3)	53.5	43.6			1.8		1.5	2.2	(3.2)		
	7	Lh	3	(1)	58.4	34.9	57.00	35.47	49	0.61	0.5	3.0	(4.6)	8	(12)
				(2)	58.5	35.5			3.0		0.5	3.0	(4.6)	±1	±2
				(3)	58.4	36.1			2.2		1.5	2.2	(3.2)		
	8	Lh	3	(1)	59.8	39.2	57.00	40.18	56	0.72	−1.0	5.1	(8.0)	12	(18)
				(2)	60.0	39.8			2.6		0.0	3.5	(5.4)	±2	±3
				(3)	60.1	40.3			1.9		0.5	3.0	(4.6)		
	9	Mi	4	(1)	61.1	39.8	58.80	40.14	.54	1.48	2.5	1.7	(2.2)	10	(15)
				(2)	61.2	40.2			2.7		1.5	2.2	(3.2)	±1	±2
				(3)	61.1	40.8			2.0		0.5	3.0	(4.6)		
				(4)	60.1	41.4					0.0	3.5	(5.4)		
	10	Ki	3	(1)	50.8	44.1	49.98	43.58	.42	0.38	1.5	2.2	(3.2)	10	(15)
				(2)	50.5	44.4			3.5		0.5	3.0	(4.6)	±1	±2
				(3)	50.1	44.5			2.5		0.0	3.5	(5.4)		
	11	Lf	3	(1)	57.2	26.8	55.84	23.86	.46	1.31	2.5	1.7	(2.2)	8	(12)
				(2)	56.8	26.9			3.2		1.5	2.3	(3.2)	±2	±2
				(3)	56.3	27.0			2.3		−0.5	4.3	(7.0)		
	*12	Kg	7	(1)	50.0	34.7	50.62	35.80	.50	0.42	−3.0	11.5	(19.0)	54	(87)
		Kh		(2)	50.7	34.4			2.9		−1.5	6.3	(9.9)	±11	±18
				(3)	51.2	34.5			2.1		−0.5	4.3	(7.0)		
				(4)	51.6	34.7					−2.7	10.7	(17.1)		
				(5)	51.9	34.9					1.5	2.2	(3.2)		
				(6)	52.0	35.4					−2.5	9.3	(15.3)		
				(7)	52.0	35.8					−2.5	9.3	(15.3)		
	13	Kh	3	(1)	52.0	37.6	50.87	37.68	.63	0.47	−1.0	5.1	(8.0)	15	(23)
				(2)	51.9	38.2			2.3		−1.0	5.1	(8.0)	±3	±4
				(3)	51.5	38.7			1.7		−0.5	4.3	(7.0)		

(*Continued*)

Table 1. (Continued)

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
VI	14	Kh	3	(1)	53.3	37.9	53.91	37.94	.43	0.26	–1.0	5.1	(8.0)	14	(21)
				(2)	53.4	38.2			3.4		–0.5	4.3	(7.0)	±3	±4
				(3)	53.7	38.5			2.4		–0.5	4.3	(7.0)		

(a) Region number in Roman numeral as marked on plate
(b) Arc number (asterisk mark is shown against that arc which does not show a monotonical increase or decrease in apparent brightness in its components)
(c) Location of arcs.
(d) Number of stars in the arc
(e) Star number in individual arcs.
(f) x-coordinate of star in mm as read on graph sheet.
(g) y-coordinate of star in mm as read on graph sheet
(h) Calculated x-coordinate of the centre of arc (ignore the last digit)
(i) Calculated y-coordinate of the centre of arc (ignore the last digit).
(j) Average separation l of components in an arc in cm (first row), the ratio Δ of average random separation (l_0 = 1.46 cm) in the field and l (second row), and the Poissonian significance $\sigma = 2 \ln \Delta$ (third row).
(k) Radius of arc in parsec (ignore the last digit).
(l) Rough estimate of the absolute magnitude of each star (±0.25)
(m) Mass of each star for the assumed q-values for single stars (ref Basu & Rana 1992).
(n) Mass of each star for the assumed q-values for multiple systems (ref. Basu & Rana 1992).
(o) Total mass of stars in an arc as per column (l), with second row giving the correction in mass arising due to error in magnitude estimates.
(p) Total mass of stars in an arc as per column (m), with second row giving the correction in mass arising due to error in magnitude estimates

3. Results and discussion

Before one claims that the constituent stars of apparent arc-like structures are physically connected structures, one has to rule out the possibility of these being a result of chance alignment of the foreground stars. In the past, in connection with the study of sprial-arm structure of the Milky Way, a lot of work was done by Th. Schmidt-Kaler and others in the 60's for the statistical significance of such claims. Many a time the claims have been refuted (see references in Th. Schmidt-Kaler, 1971), and therefore we ought to do a careful statistical analysis. Instead of studying a random distribution of stars generated by a Monte-Carlo simulation, which would have been ideal, we note that there are about 1750 stars up to magnitude 16 on the photographic plate. This corresponds to 0.47 stars per square cm on the plate. If the stars were to be randomly distributed, then the average separation (l_0) between any two stars would then be about 1.46 cm on the photograph. It is noticed that, for almost all arcs, stars forming in an arc are separated from one another by much smaller distances (l). The value of l is shown in the first entry of the j-th column of table 1, and the ratio of l_0 and l is shown as Δ in the second entry of the same column. Out of 96 arcs, stars in 91 arcs have an average separation smaller than l_0. 60% of arcs have stars with average separation one-third of the same, that is $\Delta = 3$, and 20% have it smaller than a quarter. In order to find out the statistical significance of this departure from random or change alignments, a Poissonian statistical distribution is assumed for random cases and the above departure is measured from the Poissonian probability of non-random character expressed in terms of its (Poissonian) σ-level, which can be written as twice the natural logarithm of the ratio (Δ) of average random separation (l_0) and the average separation in the arc (l). This σ-level of significance is expressed

Table 2. Single star and systemic mass-luminosity calibrations

Absolute magnitude M_V	Log of mass (m) of stars in $M_\odot$ single star log m	systemic log m	Absolute magnitude M_V	Log of mass (m) of stars in $M_\odot$ single star log m	systemic log m
–5	1.46	1.35	7	–0.18	–0.18
–4	1.25	1.15	8	–0.24	–0.24
–3	1.06	0.98	9	–0.30	–0.30
–2	0.88	0.81	10	–0.36	–0.36
–1	0.71	0.66	11	–0.45	–0.45
0	0.54	0.52	12	–0.57	–0.58
1	0.40	0.39	13	–0.72	–0.72
2	0.28	0.27	14	–0.84	–0.84
3	0.17	0.17	15	–0.93	–0.93
4	0.07	0.07	16	–1.00	–1.00
5	–0.02	–0.02	17	–1.05	–1.05
6	–0.10	–0.10			

Table 3. Frequency distribution of multiple stellar systems in the individual regions

Region No.	Single stars	Double stars	Triple stars	Quadruple stars	Total
I	67	47	11	3	128
II	74	58	19	4	155
III	186	101	21	3	311
IV	52	31	16	2	101
V	62	51	16	3	132
VI	66	45	15	3	129
Normalised to 100					
I	52	37	9	2	
II	48	37	12	3	
III	60	32	7	1	
IV	51	31	16	2	
V	47	39	12	2	
VI	51	35	12	2	

Average ratio of single : double : triple : quadruple stars ≒ 52 : 35 : 11 : 2.

in the third entry of the j-th column of table 1 against each one of the arcs. It seems that the component stars forming arcs in 3/5th of the cases at least may possibly have some close association.

We have also checked how many field stars are there on an average up to the given limiting magnitude and the given Galactic latitude. Since Eta Carinæ lies at a Galactic latitude of $b = 5°$ and the faintest stars on the plate are of the 16th magnitude, from Allen (1976) we calculate the number of stars per sq. deg. to be about 2,000 (one must also remember that the sun is located on the inner edge of Perseus-Orion arm and that between us and the Carina arm there is a relatively sparse region of an inter-arm population of particularly the intermediate mass stars). Since the size of the plate is 0.67 sq. deg., we would expect the total number of foreground stars of the order of 1200 or so. Since we see about 1,750 stars on the plate, it would mean that at least a few hundred stars belong to the nebulae itself.

We would not like to claim all these 96 arcs to be physically associated. However, it may safely be concluded that about 2/3rds of these arcs do possibly represent physical promixities, rather than chance alignments of the foreground stars. We have also identified those arcs with an asterisk mark in second column of table 1, which do not follow a monotonically increasing or decreasing order of apparent brightness from one end to the other. It can be seen from table 1 that there are only 9 such arcs. This observation is very important simply because the average mass of these component stars is greater than $2M_\odot$, while the average separation of stars in an arc is 0.25 pc, which means that the (Keplerian) dynamical time scales remains still comparably greater than the age of the Nabulæ itself and that some possible physical mechanism of fragmentation of cloudlets in a shell like structure producing knots of correlated mass distribution cannot be ruled out. So the likelihood of the chance alignments could as well be less than about 10%. On the basis of this assumption, the rest of the discussion follows.

The multiplicity counts corresponds to the ratio of the apparently identifiable single : binary : triple : quadruple stellar systems as 52 : 35 : 11 : 2, on normalisation to a total count of 100. This can be compared with the reported ratios for the field star systems in the solar neighbourhood, such as 42 : 46 : 9 : 2 due to Abt & Levy (1976) and 51 : 39 : 8 : 2 due to Duquennoy (1988). The differences are not significant. It possibly implies that field stars have their origins in some or other nebula. Without, of course, performing similar studies on other nebulæ, this cannot be ascertained. However, since the Eta Carinæ nebula is far off from us, we do not expect the components to be so well resolved, in which case, the above generalisation would imply a hierarchical fragmentation of multiple components into their own multiple components with similar frequency of the multiplicities. This possibility cannot be ruled out on its face value, as the studies of multiple stellar systems in the solar neighbourhood suggest that the typical separation of physical binaries is ~10-100 AU, rather than 0.2 pc or so.

We, therefore, examined more closely the arcs themselves in order to find evidence of having any barely resolvable (to the limit of about 0.08-0.2 pc in separation) binaries or triples. Out of 318 components in 96 arcs studied in the present work, only 7 arches contain barely identifiable binaries and one arch contains a barely identifiable triple star system. These separations are comparable to or even smaller than the radius of the Oort cloud around the sun. Only remark we can make is that such a statistics does not contradict the expectations from studies of Abt (1983), Bahcall *et al.* (1985), and Zuckerman & Aller (1986), given the short age of these stellar systems and high density environment that prevails in Eta Carinæ nebula.

The detectable, individual component stars in these arcs have their masses generally ranging between 1 and 10 $M_\odot$, a range of stellar mass which mostly ends up as planetary nebulæ, and much less frequently as supernovæ. The age of such stars cannot be less than about 30 My. The frequency distribution of the radii of the arcs are plotted in the form of a histogram in figure 3. Most of the arcs have radii of about 0.5-1.5 pc, which are well in accord with the expected shell sizes of supernova remnants in a dense cloud (Shull 1980, Wheeler *et al.* 1980, Draine & Woods 1991, for example) such as the Eta Carinæ nebula.

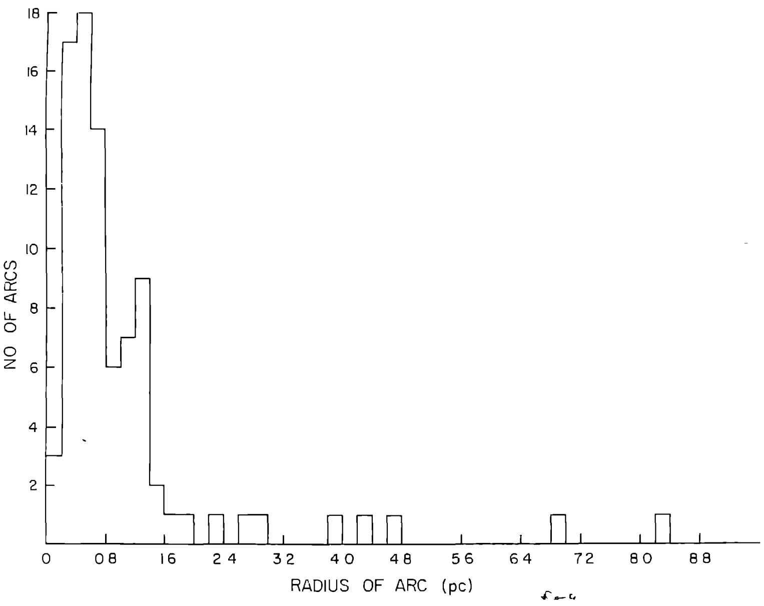

Figure 3. A histogram plotting number of arcs vs. radius of arcs in bins of 0.2 pc. The peak lies at about 0.5 pc and 90% of arcs have radii less than about 1.5 pc.

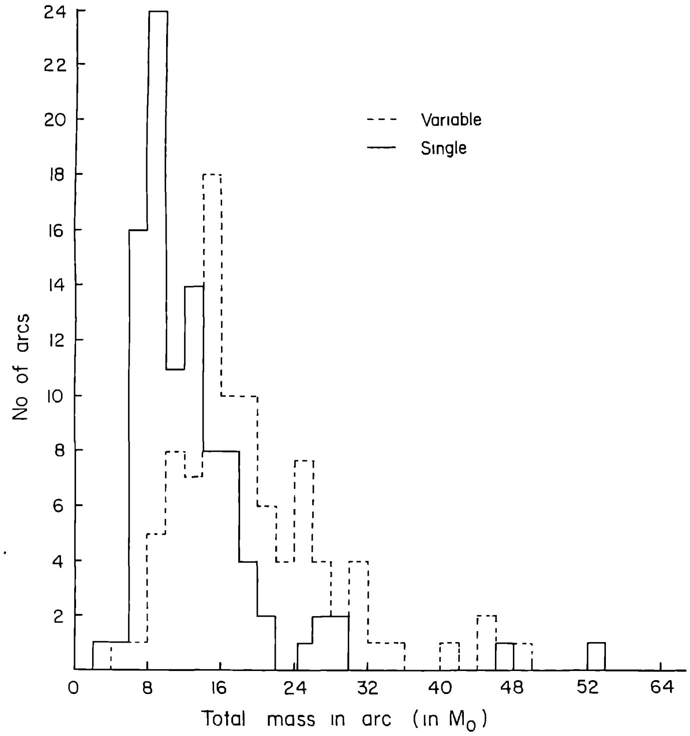

Figure 4. Histograms showing number of arcs vs. total mass of stars in the arcs, the solid one being drawn for the assumed single star for the components, and the dot-dash one for the assumed multiple proportions (M_V to mass calibrations are adopted from Basu & Rana 1992).

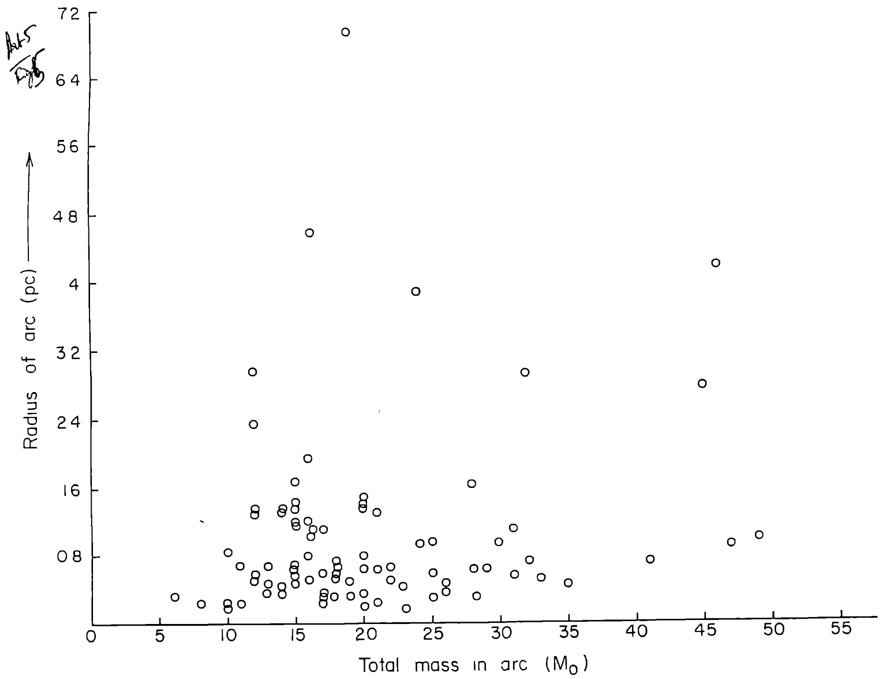

Figure 5. A scatter diagram for the possible correlation between the radii of arcs in pc and the maximum total mass of the stellar components in the arcs. Since these arcs subtend a small solid angle at their centers, the total mass swept by the blast of the supernova should have been much larger; the asymmetry observed is possibly due to the small-scale spatial inhomogeneities in the nebula.

We cannot estimate the total mass swept by such supernovæ, but the total masses accountable by the surviving stars which emerged due to fragmentation of the cloud material ahead of the shock fall in the range of 10 to 30 $M_\odot$ (see figure 4). Both these facts are more explicit in figure 5 than they do individually in figures 3 and 4. A scheme of possible gravitational fragmentation in SNR is suggested by Keto *et al.* (1991).

4. Conclusion

In conclusion, a number of statistical analyses lead us to believe that the stellar arcs, reported here, may not be the artifact of chance alignments of the foreground stars. If this is a justifiable enough conclusion, we may then apprehend further that Eta Carinæ nebula shows the marks of supernova-induced star formation almost every part of its body. May be, shock-induced star formation is the most common of all the known different processes of star formation. The relative proportions of the single, binary, triple and quadruple stellar systems in the Eta Carinæ nebula, which is lying at a distance of about 1.8 kpc, are surprisingly found to be quite similar to those of the nearby field stars. It perhaps hints at the possibility of a (two-step) hierarchical way of fragmentation of clouds into stars, triggered by an identical process. If the present study ought to imply that the blast of a supernova is the cause for star formation in the first step, then it remains as a riddle for why in the second step, the same hierarchical frequency ratios for the stellar multiplicities would prevail, unless the process of star formation in the second step is also proved to be shock-induced. This seems to be a quite puzzling aspect of the present analysis.

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