J. Astrophys. Astr. (1980) **1,** 155–164

Supernovae and the Ap Phenomenon

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Received 1980 August 22; accepted 1980 October 23

Abstract. We put forward evidence that relates the phenomenon of the chemically peculiar stars of the upper main sequence to Supernovae explosions in young clusters. In the Upper Scorpius region we find that a supernova shell has interacted with dense clouds and that the peculiar stars lie close to or along the edges of interaction.

We argue that the stars at or near the cloud faces are capable of acquiring this enriched material which is sufficiently slowed down. The magnetic accretion process of Havnes and Conti provides the mechanism of acquisition. This process with the associated magnetic braking accounts for the build-up in abundance anomalies and the slowing down of rotation with age.

Key words: Supernovae—clusters—peculiar stars

1. Introduction

Several hypotheses to explain the origin of peculiar stars exist. Catalano (1975) has reviewed critically the various hypotheses. None of the theories proposed have been able to account for the bewildering range of phenomena associated with the peculiar stars such as the range in abundance anomalies, spectral and magnetic field variations and their low rotational velocities.

The peculiar stars can be broadly divided into a magnetic and a non-magnetic sequence ranging from early F to early B stars (Wolff and Wolff 1975). The magnetic sequence consists of the Si Cr Eu Sr stars with variations in line intensity and magnetic fields suggesting a patchy surface distribution of anomalous abundances, the most anomalous being in the region of the magnetic poles. The non-magnetic sequence, in order of increasing temperature, are the Am stars, the Hg-Mn stars, the He-weak and the He-rich stars. However, these categories are not clearly defined and as spectroscopic resolution increases, one finds the characteristically overabundant elements of one group also enhanced in the others (Cowley 1975).

Among the different mechanisms proposed to explain the origin of peculiar stars, the diffusion theory proposed by Michaud (1970) is widely accepted. However, several authors have suggested that a nuclear origin of the abundance anomalies cannot be ruled out and there may be some relation between supernova events and the peculiar stars (Guthrie 1968; Blake, Schramm and Kuchowicz 1974; Kuchowicz 1975). High dispersion studies indicate that at present there is no single theory which can account for the complexity of chemical abundance patterns observed in these objects (Cowley 1975).

In what follows we suggest that supernova explosions in clusters and associations together with the magnetic accretion hypothesis of Havnes and Conti (1971) and Havnes (1974, 1975) provides the most natural explanation for the wide range of phenomena associated with these stars.

2. The Upper Scorpius region

The ring-like emission nebulosity in Upper Scorpius seen in the deep sky narrow band H-alpha photographs of Sivan (1974) is shown bounded by dashed lines in Fig. 1, which also shows the position of the H I shell and the gas clouds in this region. The velocities of various H I features from 21-cm observations by Johnson (1971) and Sancisi and Van Woerden (1970) are marked by their values. The positions of the peculiar stars found by Garrison (1967) are indicated by arrows. Table 1 lists all the peculiar stars in the Upper Scorpius region which are members of the Scorpio-Centaurus association. Table 2 lists members of the group suspected to be peculiar.

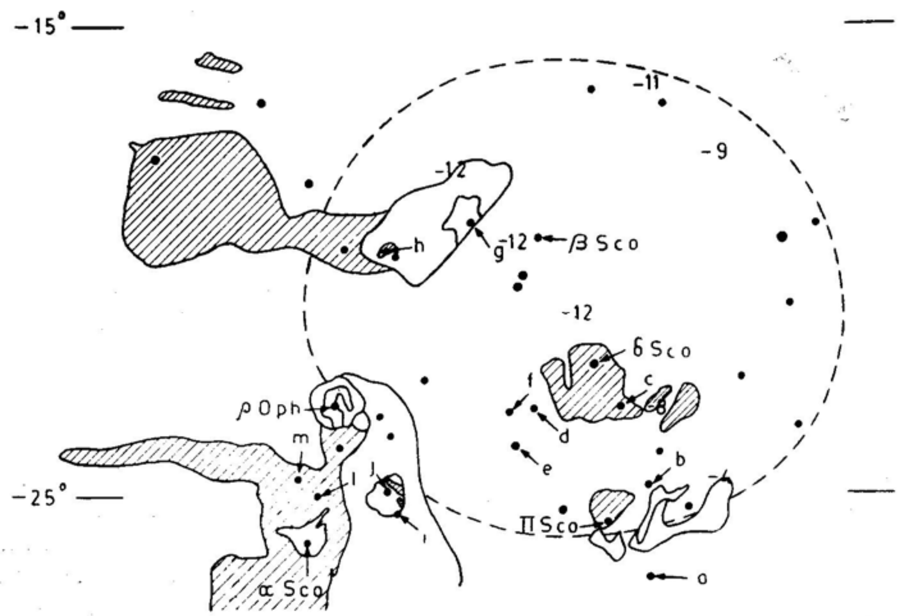

Figure 1. A schematic diagram of the Upper Scorpius region showing: (a) the peculiar stars marked by lower case letters, (b) the H I velocities by their values, (c) the position of the narrow band H-alpha emission ring by the dashed line. (d) Nebulosities in the region as depicted by Johnson (1970); shaded portions are brighter in the red Palomar Sky Survey prints and unshaded portions are brighter in the blue.

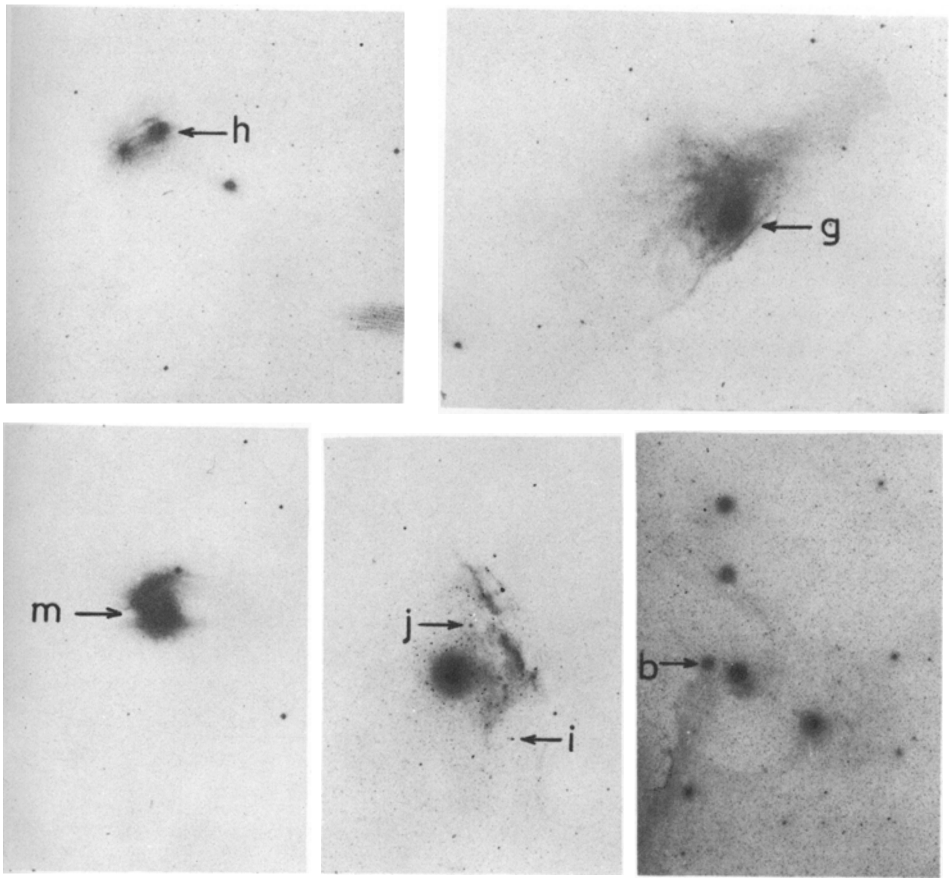

Figure 2. Enlargements of the regions around some of the peculiar stars shown in Fig. 1.

RAJAMOHAN AND PATI

Table 1. Peculiar stars in the Upper Scorpius region.

HD Number	Spectral type	*V* Sin *i*	Indicated in Fig. 1 as	Remarks
*142250	B6Vp	⩽ 50	a	SiII strong
*142301	B8p	⩽ 50	b	Q (ST) > Q (*UBV*)
*142884	B9p	210	c	SiII strong, Q (ST) > Q (*UBV*)
*144334	B8p	⩽ 50	d	Q (ST) > Q (*UBV*)
*144661	B7IIIp	75	e	Q (ST) > Q (*UBV*)
*144844	B9IV	185	f	Q (ST) > Q (*UBV*)
145102	B9p	⩽ 50		SiII strong
*145501B	B9p	—	g	Q (ST) > Q (*UBV*)
*146998	A7p (Sr-Cr)	—	i	
*147010	Ap	⩽ 50	h	Star very peculiar. See Garrison (1967) for a description.
*147105	A5p (Sr)	—	j	
147890	B9·5p	⩽ 50	—	SiII strong, Q (ST) > Q (*UBV*)
148199	Ap	⩽ 50	—	SiII strong, Q (ST) > Q (*UBV*)
*148321	A5mp (Sr)	100	l	
150035	A5p	—	—	CaII K is weak
151346	B7p	—	—	Q (ST) > Q (*UBV*)

Table 2. Stars suspected to be peculiar in Upper Scorpius region.

HD Number	Spectral type	*V* Sin *i*	Indicated in Fig. 1 as	Remarks
139160	B8Vp	165	—	The lines with the exception of Balmer lines appear weak
139365	B2.5V	135	—	Ionised Si, Mg weak; H-strong for He-type given
*142096	B2.5V	200	—	Ionised Si, Mg weak; H-strong for He-type given
145482	B2V	230	—	Spectrum indicates low luminosity at B2
*147889	B2V	100	—	Low luminosity at B2, SiII slightly enhanced
*147933	B2IV	295	—	Q(ST) > Q(*UBV*)
*147934	B2V	290	—	Q(ST) > Q(*UBV*)
*148605	B2V	250	m	Low luminosity at B2

V Sin *i* values are mean values from the determinations of Rajamohan (1976) and Slettebak (1968).

Stars marked with asterisks in Tables 1 and 2 are seen to lie at or close to the points of interaction of the shell (*i.e.* within the shell thickness) with the dense clouds in the region. These interaction edges are admittedly not very well defined in all cases. Some of the clearly defined edges are illustrated in Fig. 2, where the filaments are sometimes seen to loop around the peculiar stars.

To determine whether the peculiar stars have a distribution near or away from such interaction edges which is different from that of the normal stars or not, a chi-squared test (with continuity corrections) was carried out. All the stars in the region which are members of the Scorpio-Centaurus association (Garrison 1967) were included. Two cases were considered: Case 1, where only the stars listed in Table 1 were taken to be peculiar, giving χ_c^2 = 2·99 (P = 0·09); Case 2 where the stars in both Table 1 and

Table 2 were taken to be peculiar, giving χ_c^2 = 4·46 (P = 0·04). We give below the contingency tables:

	Case 1		Case 2	
	Normal stars	Peculiar stars	Normal stars	Peculiar stars
Away from edges of interaction	48	5	45	8
At or close to edges of interaction	34	11	29	16

It is apparent that the peculiar stars tend to lie at the edges of interaction of the shell with the dense clouds in the region.

The nebulosity (IC 4592) around ν Sco (star ' g ' in Fig. 1) has a very sharp edge as seen in Figs 1 and 2. Parts of this edge show a motion with respect to the stars of about 0·2 arcsec yr^{-1} (Johnson 1966), which at the average distance to the Upper Scorpius stars corresponds to 165 km s^{-1}. This large velocity can partly be explained in terms of an interaction of the type discussed in subsequent sections.

2.1 *Positions, Distances and Sizes*

There exists a spur of neutral hydrogen, which projects from the galactic plane through this area (McGee, Murray and Milton 1963) and as seen from the H II region produced in it by ζ Oph (not shown in Fig. 1) it appears to b e at the same distance as the latter (~ 170 pc), which is a member of the Scorpio-Centaurus association. Radio maps have also been made of this region by Sancisi and Van Woerden (1970). The maps show several H I features with velocities ranging from –9 to –12 km s^{-1} scattered over the area. The positions of these features are marked by their values in Fig. 1. Sancisi (1974) suggests that the structure and velocities of these features point to an expanding, dense, semispherical shell about 5 pc thick with a volume density of 30 cm^{-3} or higher and an expansion velocity of about 3 km s^{-1}.

The good agreement between the H I emission features and the interstellar sodium (Hobbs 1969) and calcium (Wallerstein 1967) lines for stars in the corresponding areas suggests that the H I shell is at about the same distance as these stars *i.e.* 170 pc (Blaauw 1964). The luminous and dark nebulae in this region are listed by Johnson (1970) along with the stars associated with them. These stars are all members of the Scorpio-Centaurus association (Garrison 1967, Bertiau 1958) and the clouds would hence appear to be at the same distances.

The sizes of the radio shell and the emission ring agree fairly well. Sivan (1974) estimates an angular size of 840 arcmin by 720 arcmin (which is 42 pc by 36 pc at 174 pc) for the latter while Sancisi and Van Woerden (1970) estimate a size of 15 pc by 45 pc and Sancisi (1974) gives an average radius of 13 pc for the radio shell. This discrepancy could partly be explained by the fact that most of the radio observations are on the eastern and northern side of the shell where the features are strong and sharp while the features on the western half are in general low and broad.

2.2 *The Ages of the Dense Shell and the Stars*

Estimates of the age of the Scorpio-Centaurus stars vary from $4{\cdot}5\times10^6$ (Maeder 1972) to 10^7 years (Blaauw 1964). Sancisi (1974) derives 1×10^6 years for the shell using a 'snow-plow ' model for the expansion.

The large amount of kinetic energy and momentum associated with the expanding shell system points to the occurrence of a supernova explosion (Sancisi 1974). The size of the shell is smaller than similar younger shells seen elsewhere because the ambient density here is probably an order of magnitude higher. Also we find that the star ζ Oph, considered a runaway star, has a motion which can be traced back to the approximate centre of this shell with time scales that match.

Using Chevalier's (1974) relation between the energy of a SN explosion (E_o) in an uniform medium of density n_o, the time elapsed since the explosion (t) and the radius of the remnant (R) we obtain the following values of t:

	$E_c(10^{50}$ erg)	n_0 (cm^{-3})	R (pc)	$t(10^5$ yr)
1	3	10	20	4·7
2	3	30	20	11·3
3	3	100	20	29·7
4	3	100	15	11·7
5	3	30	15	4·5
6	10	10	20	2
7	10	30	20	4·8

Values of n_o in the third and fourth rows are rather high. If we then compare the other vaues of t with the age of the stars, it becomes evident that at least one supernova could have occurred in this region.

3. The origin of peculiarities

We suggest now a likely development of events which could apply to other similar regions *e.g.* I Orion association where Kutner *et al* (1977) find that the Barnard loop has interacted with the molecular cloud complexes. The Barnard loop, has been interpreted by Reynolds and Ogden (1978) as part of an expanding shell of a supernova remnant.

The stars of the Scorpio-Centaurus association were formed out of large cloud complexes by one or more possible ways (Kerr 1976, Thaddeus 1976). On an average, stars formed from clouds by some shock or compression mechanism would be found at distances from the cloud which increase with time, the youngest stars being closest to the cloud. If one of the massive stars evolves fast and explodes as a supernova, the material ejected could, in a short time (compared to the apparent motion of the stars relative to the cloud) reach the young stars at the ' shocked ' face of the cloud. This material, rich in heavy elements and slowed down to a few km s^{-1} by interaction with the cloud, could get accreted on to the surfaces of the stars at a rate depending on their magnetic field strengths.

3.1 *The Supernovae Remnant*

The pre-supernova models of massive stars upto the collapse stage (Weaver, Zimmerman and Woosley 1978) show large enhancements for elements like Ne, Mg, Si for a 15 $M_\odot$ star. Weaver, Zimmerman and Woosley (1978) point out that during the early collapse stage about 0·15 $M_\odot$ of ^{56}Ni and ^{54}Fe+2p are produced as the collapse proceeds; this is followed by explosive silicon burning in a shell during core expansion, resulting in the ejection of material. They indicate that a 25 $M_\odot$ star can eject about 6·2 $M_\odot$ of heavy (Z>2) elements while a 15 $M_\odot$ star can eject about 1·1 $M_\odot$. Thermonuclear reactions in such supernova envelopes, caused by an intense shockwave can produce heavy element enhancements (Schramm 1973; Truran 1967).

Chevalier (1974) has discussed the evolution of the pressure, the hydrogen number density, the gas velocity and the temperature of the remnants with time (from 2 × 10^4 yr to 2·5 × 10^5 yr) for an initial ambient density n_0 (cm^{-3}) and an initial magnetic field B_0 (gauss). For n_0=1 and B_0=3 × 10^{-6}, the velocity and temperature of the shell, after it forms, decrease rapidly with time. For higher values, n_0=100 and B_0=1 × 10^{-5}, the cooling in the shell is not impeded. The ionizing radiation even in the high density cases does not impede shell formation. If the remnant interacts with a dense cloud, the kinetic energy drops sharply and most of it goes into heating up the material. The interface between the high and low density regions remains sharp. This is seen to be true for nebulosities closer to the explosion in Fig. 1 and Fig. 2 and we also notice that some of the peculiar stars are lined up along these sharp edges.

3.2 *Acquisition of Anomalies*

The magnetic accretion process (Havnes and Conti 1971; Havnes 1974, 1975) seems to be a promising mechanism for the acquisition of anomalies on the surfaces of peculiar stars. The predictions of this theory agree well with the observed abundances for the Si Sr Cr Eu stars (Havnes 1974). Also, the increase in abundance of metals with temperature is seen at least for Fe, Cr, Mn (Adelman 1973). The very large observed overabundances of Eu could be produced by this mechanism if the medium around the star was well-enriched in it. In the present scenario, this could occur if the supernova exploded in a non-uniform medium with dense clouds around and the ejecta remaining as clumpy density and abundance inhomogeneities. The large over-abundances of elements with high ionization potentials (*e.g.* Hg and Pt) is a difficulty with this theory. However, such a difficulty could be overcome if the heavy elements in the supernova ejecta are locked up in grains. The possibility of grain formation in Supernovae ejecta is discussed in detail by Schramm (1978).

Havnes (1975) considers magnetic fields at or below the detectable limit and finds that even then, large overabundances could be produced, the times required for the Hg-Mn stars being, on the average, larger than that for the magnetic stars. If, in his models one uses a largely enriched environment, the time scales could be reduced by a factor of 10 or even 100. The detailed model requires magnetospheric radii for various ionized species stemming from an interaction of the kind suggested here.

3.3 *Rotation and Magnetic Fields*

There is no apparent reason to believe that the Ap and Am stars are born differently from normal A and B stars. However, the rotational velocities of normal and peculiar stars in clusters are different. Rajamohan (1978) has given arguments to show that all main sequence single stars in clusters which are normal are also fast rotators. A summary of the rotational behaviour of peculiar stars in clusters is given by Abt (1979). Abt (1979) discusses the frequency of occurrence and the slowing down with age of rotation of peculiar stars in open clusters. The rotational velocities of Ap (Si) stars decrease sharply with age, the Am stars showing a more gradual decrease. The Hg-Mn stars also suggest a decrease but the data are insufficient to be sure. Abt also finds that these objects on the average show increased frequencies with age after an intial threshold period which is shortest for the Ap (Si) stars (*i.e.* those with the strongest magnetic fields). Any theory of the origin of peculiar stars must also be able to account for this bimodal behaviour of rotation of cluster members. Synchronisation in closely spaced binary systems cannot completely account for the slow rotation of these different groups. Even for Am stars, where the binary frequency is as high as 80 per cent, tidal effects are incapable of synchronising the orbital and rotational periods within the main sequence lifetimes of these stars (Rajamohan and Venkatakrishnan 1979, 1980). They find that rotation alone as a criterion suggests that even amongst binaries we have a normal and a peculiar sequence. It would seem that the major angular momentum losses seem to occur for the peculiar sequence in the premain sequence phase of their evolution. The differences in the magnetic and the non-magnetic sequence of peculiar stars then, apparently reflects the initial differences in the magnetic field strengths.

Dolginov (1975) has proposed a mechanism (the ‘ battery effect ’) for enhancing the observable magnetic fields as well as the abundance anomalies of peculiar stars. Any patchy abundance anomalies on the surface of the star is capable of producing a large toroidal magnetic field. Circulation of matter in this field (*e.g.* due to slow meridional circulation or tidal interaction in binary systems) even with low velocities like 10^{-4} to 10^{-5} cm s^{-1} can produce poloidal fields comparable to the toroidal one within the star’s lifetime. The chemical anomaly is supported and amplified by this field. Thus, material accreted onto the surface of the star would accelerate the operation of this process, enhancing both the magnetic field and the abundance anomalies.

From arguments given by Mestel (1975) the magnetic accretion mechanism is reasonably efficient for slowing down early-type stars; an increase in the density of the environment will improve the efficiencies of capture and braking.

This linking-up of processes provides for a fairly efficient acquisition of anomalous abundances and magnetic braking. If angular momentum loss is associated with magnetic braking, older clusters should show more slow rotating and slower rotating peculiar stars than younger clusters. This is indeed seen to be true (Abt 1979).

4. Discussion and conclusions

We see good evidence for a supernova in Upper Scorpius, which accounts well for the origin of the peculiar stars there. Similar situations probably arise in I Orion

OB (Reynolds and Ogden 1978) and CMa R1 (Herbst and Assousa 1977) and probably other areas. Supernova induced star formation seems possible in young star clusters. Can a supernova trigger the formation of a star which subsequently accretes the enriched material? Perhaps this is possible provided a newly formed star, after reaching the main sequence has an enriched environment for at least 10^4 yr, this lower limit depending on the relative velocity between the star and the material, the density and the time taken to reach the main sequence, van Rensbergen, Hammerschlag-Hensberge and van den Heuvel (1978) suggest that spectral anomalies in peculiar stars may develop in the pre-main-sequence stage itself. Considering the significant convection which may be present during this stage, the peculiarity developed, if any would be small. It would seem that stars would necessarily have to accrete the enriched material after arrival on the main sequence. Stars formed out of the enriched material itself would have a more or less uniform distribution of elements throughout the star and hence would not show up the large patchy enhancements seen on the surface.

The diffusion process (Michaud 1975 and references therein) seems to account for large overabundances in a relatively short time ($\sim 10^4$ yr). The difficulty with this process is that it requires slow rotation to start with. Also, any convection or rapid rotation results in abundances not being enhanced. However, this process could be important in maintaining the anomalies at the surface, once they are acquired.

Though the large majority of peculiar stars are slow rotators, there are exceptions where the stars are fast rotators (*e.g.* CU Vir, 56 Ari) or exhibit instabilities such as pulsation (*e.g.* Przybylski's star, 21 Com). It is generally thought that rapid rotation leads to mixing and in such cases it is not clear how the abundance anomalies could persist on the surface of the star. If pulsations are laminar then anomalies on the surface could persist, whether they were initially produced by the diffusion mechanism or by the accretion mechanism.

We have considered enriched material being accreted onto early-type stars. Is enriched material seen in spectra of nebulae in the region described? Swings and Preston (1978) have obtained slit spectrograms of the Antares Nebula around the B companion of α Sco. They find that the nebula is [Fe II] rich; Fe II, Si II and Ti II are also present while [Ni II] and [Cu II] are identified here for the first time. Lines characteristic of low density nebulae like [O II], [N II] are absent. It would seem, therefore, that this material is enriched in the metals and possibly in the heavy elements. This is probably again the supernova material lingering around the vicinity of these stars. Reeves (1972) has shown that the heavy elements enriched by the supernova can spread very fast ($\sim 10^6$ yr) but would take more than 10^8 years to mix completely with the general background.

The scenario presented above seems to explain a wide variety of observed phenomena in young clusters and associations. We interpret the blue stragglers in clusters as stars that are much more magnetic than others. The magnetic fields provide a way for reducing the central temperature and hence increase its main sequence life time relative to a non-magnetic star of the same mass. Indeed Pendl and Seggewiss (1975)'s observations that the percentage of Ap stars among blue stragglers is very much larger than that in the field further supports the phenomenon outlined above.

Acknowledgements

We are grateful to Drs M. K. V. Bappu and O. Havnes for helpful discussions. We thank one of the referees for many useful comments and suggestions. We are indebted to Mr T. P. Prabhu for help in preparation of the figures.

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