I. INTRODUCTION

1. The Be Phenomenon

In the optical region a fraction of B stars (masses in the range 5 to 25 $M_\odot$ and the surface temperatures in the range 11000 to 30000° K) display hydrogen emission lines, accompanied by emission lines of singly ionized metals. These emission line stars are distinguished from the normal absorption line B stars, with the addition of 'e' to the spectral type (Be). Be stars of all luminosity classes (V to I) show emission lines in their optical spectra. However distinction has to be made between Be supergiants and other Be stars. Be supergiants display emission lines only in H$\alpha$ (the lowest Balmer line 6562.82 Å). In general H$\alpha$ is in emission in Ia supergiants whereas in Ib supergiants, this line may be either in emission or in absorption. In case of Be stars of luminosity classes V to III not only H$\alpha$ but also higher order Balmer lines and many other singly ionized metallic lines (Fe II, Si II, Ca II, etc.) are in emission in the optical region. Apart from these emission lines many forbidden emission lines have also been detected in the spectra of certain Be stars. Generally these Be stars with forbidden emission lines (O I, Fe II, N II, S II, Fe III etc.) are called peculiar Be stars, B[e] or B[e]. Generally these B[e] stars are fainter than their normal Be counterparts. Spectroscopic studies of the B[e] stars have been carried out extensively by Cannon (1924), Swings & Struve (1941, 1945), Henize (1956), Smith (1957), Feast et al (1960), Allen & Glass (1966), Ciatti et al (1974), Ciatti & Mammano (1975), Allen & Swings (1976), Glass (1977) & Stahl et al (1983, 1984). Among the three classes of Be stars mentioned above i.e. normal or classical Be stars, B supergiants and B[e] stars, the present discussion is confined only to the classical Be stars.

Gamma Cassiopeiae was the first Be star to be discovered by A.Secchi in 1866. Only five more Be stars had been detected till 1886. Later on Merril & Burwell (1933, 1943, 1949, 1950) made a catalogue containing 1088 early type emission line stars. In 1970

In 1923 Curtis observed 11 Be stars and found that the width of the emission lines is proportional to their wavelength. In 1929 Gerracimoire found that the yellow B stars detected by Hertzsprung were characterized by enhanced emissions on the shorter wavelength side of the Balmer limit. Based on these results and using his own observational results, Struve (1931) suggested that the emission lines in Be stars arise from a gaseous outer envelope. Based on the observations of 50 Be stars he also found that the linewidth of the emission and absorption profiles were correlated. This correlation was explained as an effect of the inclination of the rotation axis with respect to the line-of-sight, which lead him to the hypothesis that the emission lines and rapid rotation of Be stars were two connected phenomena. This rapid rotation causes rotational instability and ejects matter at the equator of the flattened body of the star forming a gaseous equatorial envelope or ring around the Be star. In 1932 Struve and Swings also suggested that the envelope is moderately dense, extended and flattened at the equator. The state of ionization of the envelope is lower than that of the photosphere of the central star, as seen from the presence of emission or shell lines of Fe II in Be star spectra which are also
observed in the spectra of A type stars. Struve's model could also explain the different types of emission profiles simply as a geometric effect caused by the differences in the inclination angles of the rotation axis from the line of sight. In short the ad hoc rotational model of Struve suggests that the Be stars rotate at the critical velocity and due to the rotational instabilities, matter is ejected at the equator which forms the envelopes of Be stars. From these envelopes different types of emission line profiles are formed. To understand the physics of emission lines of Be stars many efforts have been put by different authors both from theoretical and observational point of view. References of few observational papers on Be stars between 1930 and 1970 are given below: McLaughlin (1931, 1933), Struve & Swings (1932), Morgan (1932), Williams (1934), Chalonge & Safir (1936), Rigollet (1936), Cleminshaw (1936), Greeves & Martin (1938), Boldwin (1939, 1940, 1941), Huffer (1939), Swings & Struve (1941, 1945), Barbier & Chalonge (1941), Merrill & Burwell (1943), Struve (1942, 1951), Merrill & Sanford (1944), Slettebak (1949, 1951), Holliday (1950), Wilson (1935), Wellman (1952, 1955), Edwards (1956), Boyarchuk (1958), Blaauw & Morgan (1953), Blaauw & Van Albada (1963), Lynds (1959), Kogure (1961), Abt & Golson (1966), Haggkbastl (1966), Underhill (1966), Johnson (1967), Andrews (1968), Bakos (1970), Hardorp & Strittmatter (1970), Limber & Marlborough (1968), Limber (1969), Marlborough (1969), Eggen (1969), Faraggiana (1969), Bohlin (1970), Ostriker & Mark (1968), Buscombe (1970), Doazan & Peton (1970), Page & Page (1970), Delplace (1970), Brown & Mc Lean (1977), Castor (1970), Hutchings (1971), Bahng (1971), Crawford & Barnes (1974), Kodaira (1971). The work on optical polarisation of Be stars and their photometry and spectroscopy in the radio, IR, optical, UV and X-ray bands done between 1970 and 1993 have been reported and summarised in the proceedings of IAU Symposium No. 70 (Slettebak 1976), IAU Symposium No. 98 (Jaschek & Groth 1982), IAU Colloquium No. 92 (Slettebak & Snow 1987) and IAU Symposium No. 162 (Balona, et al. 1994). Many review articles on the subject have also been published in the past. A few important reviews can be seen in Slettebak (1979), Doazan (1982), Kogure & Hirata (1982),
detailed references on the work on Be stars between 1980 and 1996 can also be found in
the Be Star Newsletters No. 1 to 32.

2. Radio Observations:

\( \psi \) Per (HR 1087, HD 22192) is the first Be star to be detected in radio at 6 cm
wavelength using the VLA (Taylor et al 1987). It was found that the spectral slope of the
continuum of this star is steeper than that found from IRAS (12 to 100 \( \mu \)m) data. (Taylor
et al. 1990). Searches for radio emission from new Be stars were made at 2 cm using the
VLA, based on IRAS - selected Be stars and radio emissions were detected from another
5 Be stars. The radio spectral index of these 5 Be stars were also found to be significantly
steeper than that of IR (12 to 60 \( \mu \)m) spectral index. Usually the radio spectral index value
is greater than 1 \( (\alpha_{\text{radio}} > 1) \) and the value of IR spectral index is in the range of 0.6 to 1
\( (\alpha_{\text{IR}} \sim 0.6 - 1) \). In 1990 Apparao et al. (1990) observed 18 Be stars in the radio
continuum at 2 cm wavelength with the VLA and made simultaneous optical observations
at VBO to confirm the differing spectral index at the radio and IR regions but could not
detect any radio emission from them. Subsequently Waters et al. (1991) observed 6 Be
stars at 0.8 and 1.1 mm for which radio data from VLA observations were available and
confirmed the differing spectral slopes for these stars. From these results it was found that
the spectral turnover usually takes place in the sub-mm wavelength range.

3. Infrared Observations

From radio observations it has been found that the the envelopes of Be stars are extended
to several hundreds of stellar radii. This gives the impression that the gas envelopes
around the Be stars expand very slowly. Also from these envelopes infrared emission both
in the near IR region (1 to 10 \( \mu \)m) and the far IR region ( >20 \( \mu \)m) has been observed. For
more than a decade it is known that the IR emission from a Be star, when it is in Be phase, is usually more than that due to the star in its B phase (Doazan 1982). This excess infrared emission is generally believed to be due to the free-free and free-bound emission from the ionized gas in the envelope of Be stars. Based on this idea Waters et al. (1987) carried out infrared observations using IRAS satellite to detect IR emission for different spectral types of Be stars and many such stars were detected at 12µm, 25µm, 60µm and 100µm (Lamers 1987a, b). These observations have clearly shown that the spectral type, projected rotational velocity, Hα emission and optical polarization are clearly correlated with the IR excess (detailed references can be found in Lamers 1987a, Waters & Marlborough 1994). From IR observations of Be stars many infrared lines (Paschen series, O I (λ 7774 Å, λ8446 Å), Ca II triplet (λ 8498 Å, λ8542, 8662 Å), Fe II ( 7712 Å), Brackett lines and He I (1.08 µm)) have been detected in their spectra. The Ca II infrared triplet emission lines of Be stars have displayed no correlation between their emission intensities and any other parameter of these stars (Polidan & Peters 1976, Polidan 1976). It was suggested by Polidan & Peters (1976) that such non-correlation between Ca II triplet lines and Be star parameters may be due to interactions within a binary system. However Briot (1981) found that the Be stars showing emission in Ca II triplet also display infrared excess and that this infrared excess is slightly higher for these stars than for those without Ca II triplet emission. Using these observations several attempts have been made to model the atmospheres of Be stars (Bjorkman & Cassinelli 1993, Bjorkman 1994, Owocki et al. 1994, Waters & Marlborough 1994). However the origin of the IR excess is still not clearly understood. It may be mentioned that the IR excess may be due to the heating of the gas without ionization by the C-shocks which produce the observed IR luminosity without Hα emission (Apparao et al 1993).
4. Optical Observations

Most of the work on Be stars have been carried out in the optical region. As it is difficult to summarise all these works in a few pages only the results obtained from these observations of Be stars are being summarised below.

4.1. Photometric Variability

It is known that the Be stars exhibit brightness variations on different time scales (Feinstein & Marraco 1979, Hirata & Hubert-Delplace 1981, Hirata 1982). Detailed references on photometric studies on Be stars can be found in Mendoza (1982). It has been found that the brightness of Be stars usually vary by about 0.05 magnitude within a day and around 0.1 to 0.2 magnitude on a month timescale and 0.3 to 0.4 magnitude on the timescales of years or longer. Results obtained from the long term variability studies show that the early type Be stars become redder when the brightness increases and the inverse phenomenon has been found in the late type Be stars i.e. they become bluer when they are in relatively brighter phase. A large fraction of Be stars have displayed periodic brightness and line profile variations with the timescale of one day. The physics of these periodic variations is not yet clearly understood. However these variations have been attributed to non radially pulsation (NRP) or rotational modulation (RM) (Baade 1987, Harmanec 1987, Percy 1987 and Baade & Balona 1994).

4.2. Variability of Emission Line Intensity:

From the study of emission line variabilities of Be stars, especially in Hα line it has been found that early type Be stars display intensity variations of emission lines on a shorter time scale than the late type stars (Hirata et al 1981, Hubert-Delplace 1982). It has also been found that the phase variations involving transitions between B, Be, and Be shell
phases of the Be stars take place on a 10 to 20 years time scale and the emission line intensity variations are very dominant during the Be phase.

4.3. Violet to Red emission strength variability (V/R):

From the pioneering work of Copeland & Heard (1963), it was found that most of the Be stars display V/R variations which were of quasi-periodic nature with a mean period of about 6 to 8 years. Hirata & Hubert-Delpalce (1981) confirmed the above results based on the observations of 28 Be stars. Usually the V/R variations occur on a shorter time scale than that of the E/C variations. The V/R variations of the emission lines of Be stars have been reported to occur in hours, days and months (Slettebak & Reynolds 1978, Dachs et al 1981, 1986a, Slettebak 1982a, Kogure et al. 1982 and Ghosh 1989). It has also been found that the values of V/R are different for different lines of the same star (Delplace & Chambon 1976, Slettebak 1982b, Kogure et al. 1982, Kogure & Suzuki 1984, Ballereau & Chauvelli 1989, Apparao & Tarafdar 1986, Hubert et al. 1987, 1988, Doazan et al. 1989, Horaguchi et al. 1993, Telting et al. 1993, Mon et al. 1992, Koubsky et al. 1989, Okazaki 1991). It has been found that the emission intensity of Balmer lines (Hα and Hβ) varies in concert with the brightening of Be stars and vice versa (Dachs 1982 and Mon et al. 1992). Similar type of correlations have also been found in Be stars between the brightness of the star and the V/R variations and vice versa (Hirata & Hubert-Delplace 1981, Hubert-Delplace et al 1982).

4.4. Spectral Energy Distribution

From the continuum energy distribution of B and Be stars it has been found that the depths of the Balmer discontinuity diminishes in Be stars as compared to those of B type stars of similar spectral type (Barbier & Chalonge 1939, 1941, Chalonge & Divan 1952, Gutierrez-Moreng et al. 1968, Schild 1976, 1978, Divan 1979, Underhill et al 1979,
In addition, two Balmer jumps have been found in the spectra of Be stars as compared to the single Balmer jump in B type stars. It has been found that among the two Balmer jumps of Be stars the first Balmer jump did not vary while the second one displayed variability. These results of two Balmer jumps strongly suggest the presence of two regions in the atmosphere of Be stars - the stellar photosphere giving rise to the first normal Balmer jump and the second Balmer jump being due to the extended envelope of low gas density around these stars (Divan 1979, Divan et al 1982).

4.5 Optical Spectroscopy

From the high resolution spectroscopy of Be stars many emission lines have been detected and they are mainly Balmer lines, Fe II lines, He I lines and Si II lines. These lines have displayed a variety of profiles which can be classified into two groups: symmetrical line profiles and asymmetrical line profiles. Again each group can be divided into four subgroups which are shown in Fig. I.1. The classification of Hα profiles of Be stars is in agreement with the classification scheme of Hanuschik (1995). From these figures it can be seen that these variety of profiles are mainly the manifestations of the inclination effect and other effects like optical depths and kinematics (Struve 1931, Merrill 1949, Kogure 1969, Delplace 1970, Kogure et al 1978, Poeckert & Marlborough 1978a, b, 1979, Ebberts 1980, Andrillat & Fahrenbach 1982, Fontaine et al 1982, Kogure & Hirata 1982, Slettebak 1982b, Barker 1983a, b, Andrillat 1983, Hubert-Delplace 1983, Hirata & Kogure 1984, Mullan 1986, Doazan et al 1984, Dachs et al 1986a, b, Peter 1986, Barker 1986, Hanuschik 1986, and Hanuschik 1995). Based on the spectra obtained from medium dispersion prism spectrograph Struve suggested a flat rotating equatorial disk or envelope with relatively large optical depth for line emission along the equatorial plane of the disk. Long after Struve's work Dachs et al. (1977) took up a program in 1974 for the
Fig. 1.1 Symmetrical and asymmetrical line profiles of the four classes of emission profiles.
systematic studies of the emission lines of Be stars to understand the dynamics of the
envelope of these stars. The program was continued by them for more than a decade
(Dachs et al 1981, Dachs & Hanuschik 1984, Dachs et al 1986a, b). Another such
program was undertaken by Mennickant et al. (Mennickent & Vogt 1988, Mennickent et
al. 1994) and also by Slettebak et al. (1992).

From the above studies the following results were obtained.

1. Emission line half-widths generally increase with increasing vsini of the star, and for
stars showing variable emission they decrease with increasing equivalent width.

2. The peak separation in the emission lines is frequently visible with higher order Balmer
lines and also with weak H\alpha emission lines.

3. The half width of H\alpha emission line (km s\(^{-1}\)) is larger than that of H\beta of the same star.

4. Variation of the equivalent widths of H\alpha have been observed on the timescales of one
day to several years.

5. For a particular range of projected rotational velocity, the half width is inversely related
to the equivalent width through the equation \( H(\alpha) \propto [-W(\alpha)]^{1/4} \).

6. Usually Balmer line emitting region lies in the range of 7 to 20 stellar radii and this
region has a temperature of around 10000° K with electron densities in the range of \(10^{11}\) to \(10^{13}\) cm\(^{-3}\).

7. Be stars with weak emission have a somewhat flatter Balmer decrement than stars with
strong emission. Early type Be stars have flatter Balmer decrement than the late type Be
stars.

8. Linear continuum polarisation upto 2% has been detected in Be stars. It is believed that
the polarisations are due to the electron scattering, with a wavelength dependence due to
absorption and reemission by partially ionised hydrogen. Polarisation results suggest that

4.6. Optical Interferometry

Hanbury Brown and his collaborators were the pioneers in the high optical resolution studies, of early-type stars including Be stars, around 1960s using the Narrabri Stellar Interferometer in Australia (Hanbury Brown et al. 1970, 1974a, b; Cassinelli & Hoffman 1975). Around mid-1970s, Hanbury Brown and his collaborators tried to resolve the envelope of Be stars in Balmer lines (Hanbury Brown et al. 1974b), but their results were not very encouraging and they concluded that a much more sensitive interferometer was required. In 1970, Labeyrie invented a new instrumentation and technique (Speckle Interferometry) for measuring the geometry of Be star envelopes (Labeyrie 1978). Using this technique Blazit et al. (1977) were able to obtain the limits on the apparent diameters of the envelopes of Be stars in Balmer lines. Many spectroscopic binaries with a B or Be component were resolved from speckle observations (Labeyrie et al. 1974, Bonneau et al. 1980, Mc Alister & Hartkopf 1988). At present other techniques like Differential Speckle Interferometry, Optical Long Baseline Interferometry, etc. are getting ready to attain sub-milliarc second resolutions which will enable us to obtain many exciting results on Be stars (detailed references are given in recent reviews by Vakili 1994 and Robertson & Tango 1994).
5. Ultraviolet Observations

The picture of Be star envelopes resulting from the ultraviolet observations is strikingly different from that of radio, infrared and optical observations. The ultraviolet observations show evidence for highly superionized regions with temperatures of the order of $10^4$ °K. Far from being quiet they are the site of violent ejections of matter which are highly variable. High dispersion ultraviolet spectra of Be stars with IUE have revealed conspicuous changes in the profiles of C IV, Si IV, Si III and Al III. These profiles have displayed both short term (on the time scales of hours) and long term variations (on the time scales of months to years). These variations are well correlated with recurrent and episodic mass loss of these stars. (Grady, et al 1989, Doazon et al 1989, Prinja 1989, Percy and Peters 1991, Bopp et al 1991, Gies 1994). Based on the UV data the wind-compressed disk model (Bjorkman & Cassinelli 1993, Owocki et al 1994) has been developed to accommodate the existence of both cool circumstellar envelope, which explains the optical properties of Be stars along with the superionized wind which was found from UV spectroscopy. However this steady state model is unable to explain the irregular variabilities of Be stars.

6. X-Ray Observations

Maraschi, Treves & van den Heuvel (1976) found, for the first time, that Be stars are ubiquitous amongst the transient X-ray sources. Some of these Be X-ray sources were very bright and displayed X-ray pulsations. Such pulsations indicated the presence of a compact object (a white dwarf or a neutron star or a blackhole) orbiting around the Be star. It was also suggested that the transient X-ray source is due to the accretion of gaseous materials, ejected from the Be star, by the compact object. Be X-ray sources usually emit hard X-rays between 1-20 keV energy range. However, from recent ROSAT survey, many new Be X-ray sources have been detected in the soft X-ray (0.1-2 keV)
range (Meurs et al. 1992). The X-ray luminosity of these soft Be X-ray sources is around \(10^{32}\) erg s\(^{-1}\). It has been suggested that the soft X-rays originate from radiatively driven wind, from the Be star in its B-phase, heated by shocks (detailed references can be seen from Apparao 1994).

7. Models of Be stars

Based on the above results, different models of Be stars have been developed to explain their physical properties. The different models are: (i) the rotationally enhanced stellar model (Marlborough 1987), (ii) Be stars as interacting binaries (Harmanec 1987), (iii) Be stars as non radial pulsators (Baade 1987, Gies 1994, Saio 1994), (iv) the spheroidal/ellipsoidal variable mass loss decelerated Be star model (Doazan 1987), (v) magnetical loop model for Be stars (Underhill 1984, Smith 1994), (vi) rotation modulation model of Be stars (Balona 1990, Baade & Balona 1994), (vii) wind-compressed disk model (Bjorkman & Cassinelli 1992, 1993, Bjorkman 1994). All these models are able to explain certain observed properties of Be stars. However they are are unable to explain the irregular behaviour of these stars. We also do not understand many physical phenomena like the phase variations, origin of mass loss, geometry and dynamics of the envelopes, irregular and quasi-regular variations of disk structure, rotational and radial motions of the envelope, the relation between the circumstellar disk and the properties of the underlying stars etc. of the Be stars.

8. Present Study

The present study was initiated to obtain very high-resolution and high signal-to-noise ratio spectra of as many Be stars as possible so as to be an aid in understanding the observed peculiarities of Be stars. Polarimetric observation of selected Be stars have also been done with near-simultaneous spectroscopic observations, providing an important tool
in understanding the shape of the circumstellar gaseous envelope in Be stars. Due to the enormous amount of effort and time needed in obtaining such a large sample of good quality data spread over a sufficiently long time interval, the scope of the present study has been restricted to the analysis of certain statistical properties of the envelopes without going into much deeper study of various aspects of the problem. Anyhow it is hoped that the vast amount of data collected, will be an invaluable reference source for all future work on Be stars whether theoretical modelling or observational studies.

All the observations were done at the Vainu Bappu Observatory, Kavalur using the 1m and 2.34 m telescope equipped with a computerised data acquisition system with a liquid nitrogen cooled CCD detector. Polarimetric observations were done with a sky chopping polarimeter attached to the 1m telescope. The instrumentation and the data reduction procedures are described in the second chapter.

The third chapter describes in detail the spectroscopic studies of 163 Be stars observed over a seven year period forming the largest sample studied so far. An atlas of high resolution (0.17 Å pixel$^{-1}$) and high signal-to-noise ratio (S/N ~ 150-200) CCD spectra of the above 163 Be stars in H$\alpha$ (6562.82 Å) and H$\beta$ (4861.34 Å) is presented. The values of V/R, the equivalent width (W), and Full Width at Half Maximum intensity (FWHM) and peak seperation ($\Delta V_{peak}$) are reliably determined using IRAF package installed in the SUN SPARC CLASSIC workstation at VBO, Kavalur and are presented in this chapter. The correlation between the various measured parameters and the inferences drawn from them regarding the nature of the envelopes of Be stars are also presented in this chapter.

In the fourth chapter the results of the spectroscopic observations of 58 A/Ae- and Be-shell stars are presented. The line profiles of these shell stars have been studied and from the correlations obtained between the various measured quantities important conclusions
have been drawn regarding classification of shell stars and the nature of their discs. These are presented in this chapter.

The results of the polarimetric observations of 29 Be stars done almost simultaneously with the spectroscopic observations are presented in the fifth chapter. The polarimetric observation were done at the B, V, R, I pass bands. The percentage of polarization and its variation with wavelengths have been studied and its bearing on the shape of the circumstellar envelope is analysed and presented in this chapter.

The last chapter summarises the major results of these studies. So far, not only the origin, but even the geometry of Be star envelopes is still under dispute. The large number of Balmer emission line profiles obtained have been analysed to study the average properties of envelopes surrounding Be stars and their trends of variability. The bearing of the line profiles on the dynamics of the stellar envelopes is discussed in detail. The almost simultaneous polarimetric and spectroscopic observations indicate reliably the flatness of the circumstellar envelope of the Be stars, since most of the stars exhibit intrinsic linear polarization of about 2% in the optical continuum. The importance of continuing this study and the need for much more detailed analysis of the data obtained here has also been highlighted. It is expected that the analysis given in this thesis would help in understanding the spectroscopic and polarimetric properties of Be stars. The atlas will provide an useful empirical basis for planning observation of Be stars from space and ground, and that it will be used as a tool for future research on these subjects.