Chapter 1

Classical Be stars

1.1 Introduction

A Classical Be star (CBe) is a rapidly rotating B-type star with an equatorial circumstellar decretion disk, which is not related to the natal disk the star had during its accretion phase (Porter and Rivinius, 2003). Struve (1931) suggested that rapidly rotating single stars of spectral class B are unstable, which eject matter at the equator, thus forming a nebulous ring which revolves around the star and gives rise to emission lines. The present working definition of a Be star is given as a non-supergiant B star whose spectrum has, or had at sometime, one or more Balmer lines in emission (Collins, 1987). The term classical has been used to distinguish them from Herbig Ae/Be (HAeBe) stars, which are intermediate mass (2–10 M_\odot) pre-main sequence (PMS) candidates with circumstellar accretion disk. From here onwards CBe/Be is used to represent classical Be stars. Recent studies point out that Be stars are not rotating at critical velocity and the circumstellar disk is formed by episodic mass loss from the central star. CBe stars rotate at 70–80% of their critical velocity and hence the reason for the formation of disk may not be equatorial mass loss mechanism. Jaschek and Jaschek (1983) identified 12% of the stars in the Bright Star Catalogue as Be stars. The consensus is that the highest fraction of Be stars appears around early spectral type.

The schematic diagram of a Be star is shown in figure 1.1 (Kogure and Hirata,
1982). CBe stars falls into 3 categories based on the viewing angle. They are normal Be stars (non-supergiants), B-type shell stars and Pole-on stars (Kogure and Hirata, 1982; Jaschek et al., 1981). Normal Be stars (non-supergiants) show double-peaked emission lines whose central reversals are not deeper than the continuum. B-type shell stars are characterized by shell lines in Balmer lines and metallic lines from ground states or metastable levels. The properties of shell lines are that they are usually sharp and their central depths are usually deeper than the continuum. Pole-on stars are characterized by single-peaked emission lines on broader photospheric absorption lines. They also show narrow He\textsuperscript{i} absorption lines. Pole-on stars are seen in the direction of rotation axis while shell stars are seen at an inclination angle of 90\(^\circ\), along the equator (Hirata and Kogure, 1984; Porter, 1996). The schematic diagram showing the Balmer line profiles of above mentioned categories of Be stars is given in figure 1.2 (Kogure and Hirata, 1982).

Conventionally the mass and radius were determined for Be stars which were part of eclipsing binary systems. But the problem here is that these systems are semi-detached/interacting binaries, which result in unreliable estimations. However, Popper (1980) estimated the masses and radii of Be stars in the spectral range B0–B8 as 16–3.5 M\(_\odot\) and 7–2.7 R\(_\odot\) respectively.

The properties of Be stars can be summarized as
1. Be stars are one of the fastest rotators in the Galaxy (\(v\sin{i} > 100\) km/s) which rotate close to the critical limit, where the centrifugal force balances gravity, as first stated by Struve (1931).
2. Emission lines are present in optical and infrared spectra indicating the presence of a circumstellar envelope (Struve, 1931). The circumstellar regions are cooler (electron temperature \(\leq 10^4\) K) than photosphere and the electron densities are of the order of \(10^{11}\) to \(10^{12}\) electrons per cm\(^3\). The mass loss rate derived from Infra-red (IR) measurements is about \(10^{-8}\) M\(_\odot\)/year (Hartmann, 1978; Waters, 1986).
3. The study of resonance lines in ultraviolet spectra of early Be stars indicates high velocity (500–1000 km/s), rarefied (10⁹cm⁻³) polar winds with a mass loss rate 10⁻¹⁰ M☉/year (Snow and Marlborough, 1976; Snow, 1981). The mass loss rates and density in polar region are about 100 times less than equatorial value. This suggests that the winds of Be stars are asymmetric (Waters et al., 1987).

4. Be stars show photometric and spectroscopic long and short term variability (Doazan and Thomas, 1982).

### 1.2 Be phenomenon

Although it has been 143 years since Father Angelo Secchi discovered first Be star (γ Cassiopeia), the Be phenomenon still eludes explanation. Be stars are normal B-type stars with an optically and geometrically thin circumstellar disk, which is inferred from emission lines, IR excess and intrinsic polarization. The ‘Be phe-
nomenon’ is the episodic occurrence of mass loss in these stars, resulting in Balmer emission. While the Be phenomenon can be observed in some late O and early A stars, it is mainly confined to stars of B spectral type. The production of disk in CBe stars is still a mystery and majority of the studies point towards an optically thin equatorial disk formed by channeling of matter from the star through wind, rotation and magnetic field (Porter and Rivinius, 2003).

Rapid rotation, stellar wind, non-radial pulsation, magnetic field and binary interaction are the proposed mechanisms to explain Be phenomenon in Be stars. In the following subsections each of these mechanisms are discussed.
1.2.1 Rapid rotation

Be stars rotate faster than normal B stars, although they do not rotate at break-up velocity (Slettebak, 1979). The effect of rotation in the evolution of massive stars is not fully understood. The outer layers of rotating massive stars may spin up due to the evolution of the angular momentum distribution (Langer and Heger, 1998; Heger and Langer, 2000). When the star rotates at critical speed, it reaches $\omega$ limit, and the effective gravity becomes zero (Maeder, 1999). It has been found that Be stars rotate only at 70% of critical velocity ($V_{\text{crit}}$) (Chen and Huang, 1987; Porter, 1996). By taking the effects of equatorial gravity darkening, Townsend et al. (2004) argued that Be stars may be rotating close to critical velocity. Gravity darkening is the phenomenon in which fast rotation produces equatorial stretching of stars, which in turn induces non-uniform surface gravity and temperature distributions (von Zeipel, 1924). Using Monte Carlo modeling Cranmer (2005) found that late type Be stars (B3 and later) can rotate close to $V_{\text{crit}}$ while early type rotate at 40–60% of the critical value.

From an analysis of 183 stars brighter than $V = 6$ mag, Slettebak (1982) found the distribution of Be stars to peak in B2 spectral type. The mean $v\sin i$ values for both main sequence (MS) and luminosity class III and IV Be stars were found to be in the range 200–250 km/s (Slettebak, 1982). The full width at half maximum (FWHM) values of the line profiles are used to estimate rotation velocity, which is the azimuthal component of velocity. The rotation velocity can be calculated by treating the circumstellar disk to be Keplerian or non-Keplerian. Hummel and Vrancken (2000) found that the line profiles produced using a Keplerian disk is indistinguishable from angular momentum conserving disk by changing the density structure of the disk. They found the value of rotational parameter ‘$j$’ to be less than 0.65 in the relation for rotation velocity, $V_\phi \propto R^{-j}$, where $\phi$ is the azimuthal angle. This value is quite near to the Keplerian value, which is $j = 0.5$. Apart
from azimuthal velocities, radial velocity component is used to understand the disk formation and dissipation process. The line profiles from shell stars have been used as diagnostics of radial outflow.

1.2.2 Stellar winds

A stellar wind is the continuous, supersonic outflow of matter from a star. In massive stars, the winds (driven by radiation pressure) influence the star’s evolution as well as the interstellar medium. The circumstellar material in Be stars is concentrated in a disk with a high density and relatively low temperature. In the polar regions of the star the mass flux is lower which produces a low density wind with large velocities (typically 1000 to 2000 km/s). The super-ionization occurs in this low density wind (Poeckert, 1982). This model does not explain why the Be phenomenon can vanish and re-appear on timescales of the order of years. An alternative model was proposed by Doazan and Thomas (1982). They assume that the Be star is surrounded by a spherically symmetric corona, in which the material can be accelerated to large velocities of the order of 1000 km/s. Outside this corona the wind is decelerated by interaction with the circumstellar material. This produces a very extended region of moderately high density, which produces the H$_\alpha$ emission. In this model the long time scale variations of the emission line phenomena are explained by the presence or absence of the material which is collected in the decelerating region. The wind compressed disk (WCD) model of Bjorkman and Cassinelli (1993) proposes the formation of dense equatorial disk by radiation-driven wind, in which the ram pressure of the polar wind compresses and confines the disk. However it has been estimated from numerical hydrodynamic simulation that the disk generated by WCD model is not dense enough to produce enough IR/radio continuum emission (Owocki et al., 1994).
1.2.3 Non-radial pulsations

Be stars are found to occupy the same region in the HR diagram as β Cephei and Slowly Pulsating B-type (SPB) stars. Hence it is assumed that the pulsation belongs to p and/or g-mode driven by the κ (kappa) mechanism associated with the Iron bump. The rapid photometric and spectroscopic variability in Be stars has been attributed to non-radial pulsations (NRP) phenomenon (Baade, 1982; Rivinius et al., 2003; Rivinius, 2007). The wave-rotation interaction in rotating systems was examined by Ando (1982) and he showed that differential rotation can be amplified by a redistribution of angular momentum, through the transfer of energy from wave (NRP) to rotation. Cranmer (2009) developed this idea and proposed the formation of dense Keplerian disks in Be stars even if the underlying photosphere is rotating at 60% of critical velocity. The possible connection between pulsation and episodic mass loss in Be stars has been explored by various authors (Baade, 1985; Ando, 1986; Osaki, 1986; Townsend, 2007). Another proposed mechanism for the formation of disk is by episodic ejections of material from some specific region on the star (Kroll and Hanuschik, 1997; Owocki and Cranmer, 2002).

The early type Be stars exhibit line profile variability (lpv) in absorption over a period of 0.5 to 2 days. Rivinius et al. (2003) analysed 3000 high resolution spectra of 27 early-type stars and assigned short term variability to NRP, with most of them favoring \( l = m = +2 \) pulsation mode. They have demonstrated that the appearance of lpv depends mostly on the projected rotational velocity, vsini. The Be star \( \mu \) Cen has been used to study the correlation between stellar pulsation and disk formation (Rivinius et al. 1998a; Rivinius et al. 1998b). The input of mass and angular momentum by the star onto the disk was demonstrated by the beating in phase of multiple NRP periods with outbursts of circumstellar material. Štefl et al. (2003) demonstrated that similar kind of outbursts can be seen for Be
stars with single pulsation period, like in the case of \( \omega \) CMa. Hubert and Floquet (1998) showed that pulsations in B6-B9 type stars are much less common than in their early-type counterparts. Baade (1989) did not detect \( lpv \) in the spectra of B8–B9.5 Be stars while Saio et al. (2007) found low amplitude g-modes in \( \beta \) CMi, which is a B8Ve star. Diago et al. (2009a) detected g-mode pulsations in B8IVe star HD 50209 from time series analysis of photometric data observed by CoRoT (Convection, Rotation and planetary Transits) space mission. It can be inferred from these observations that some Be stars might exhibit NRP which plays a critical role in the mass ejection mechanism.

1.2.4 Magnetic field

Intermediate and high-mass stars are mostly non-magnetic with a few percent (depending on the spectral type) showing detectable magnetic fields (Landstreet, 1992). Cassinelli et al. (2002) proposed a magnetically torqued disk model for Be stars, in which a strong magnetic field of \( \sim 300 \)G channels the flow of wind material to form an equatorial circumstellar disk (Poe and Friend, 1986; Ud-Doula et al., 2008). The magnetic rotator wind disk model proposes the formation of Keplerian disks around Be stars by magnetic fields of the order of a few tens of Gauss (Maheswaran, 2003, 2005). Maheswaran and Cassinelli (2009) proposed that magneto-rotational instability can assist the formation of quasi-steady disk, for a magnetic field of a few tens of Gauss.

The magnetic field in Be stars are detected through spectropolarimetry, from Zeeman splitting of spectral lines. The result of the measurement of circular polarization is usually described by deducing the mean longitudinal field, \( < B_z > \). Recent development in observations is the detection of magnetic field in the range 40–150 G for eight CBe stars using FORS1 instrument installed at VLT.
these stars, $\lambda$ Eri shows a cyclic variability in magnetic field and the period was found to be 21.1 minutes (Yudin et al., 2009). Hubrig et al. (2009) detected weak magnetic fields in four Be stars, HD 62367, $\mu$ Cen, o Aqr and $\epsilon$ Tuc with HD 62367 having a strong longitudinal field, $< B_z > = 117 \pm 38$ G.

1.2.5 Binarity

Kriz and Harmanec (1975) presented a general hypothesis that a large portion of Be stars are interacting binaries undergoing mass transfer from the secondary component filling its Roche lobe. Harmanec (1985) proposed that the unstable secondary contracts towards the helium MS, since most of the Be stars lack detectable secondaries. Gies (2001) categorized Be binaries in four groups (1) hot Algols (i.e. interacting binaries which were the essence of the hypothesis by Kriz and Harmanec (1975)), (2) Be + He stars (binary model modification by Harmanec (1985)), (3) Be X-ray binaries and (4) Be + white dwarf (WD) combinations (Koubský, 2005).

About 70% of the evolved Be binary systems should have a white dwarf companion, 20% a helium star (sdO) and 10% a neutron star (NS) (van Bever and Vanbeveren, 1997; Raguzova, 2001). About 30 Be/X-ray binaries with a NS companion has been detected (van den Heuvel and Rappaport, 1987). The Be + WD binaries can be identified as low luminosity X-ray sources and despite the large predicted number none has been discovered yet. The only confirmed candidate belonging to Be + sdO class is $\phi$ Per (Gies et al., 1998) while more evidence is pouring in to include 59 Cyg (Maintz et al., 2005; Rivinius and Štefl, 2000) and HR 2142 (Peters, 1983; Peters and Gies, 2002). Plavec and Polidan (1976) pointed out the close relationship between Be stars and Algol eclipsing binaries and concluded that mass transfer in Algols of longer periods may probably produce a Be star. Since binarity is not confirmed in many Be stars, it is now generally accepted that Be stars can be formed as single stars and in binaries.
1.2.6 Role of stellar evolution in Be phenomenon

Schmidt-Kaler (1964) claimed that Be phenomenon occurs during the overall contraction phase following the exhaustion of hydrogen in the core. Hardorp and Strittmatter (1970) cast some doubts on this claim and showed that one observes a larger percentage of Be stars than allowed by the small fraction of the MS lifetime spent in this particular phase. Schild and Romanishin (1976) concluded that the fraction of Be stars remains constant during 80% of the MS phase, but undergoes a four-fold increase at the onset of the core contraction phase. Stars in this phase were identified with the extreme Be stars (Bex) by Schild (1966), who identified the spectroscopic features that characterize them. Slettebak (1985) stated that Be stars may be found above the zero-age main sequence (ZAMS) because of evolutionary effects, envelope reddening or rotationally induced gravity darkening of the underlying star, or some combination of the three. Keller et al. (2000, 2001) found most of the Be stars close to the turn-off of the star clusters they observed. Fabregat and Torrejón (2000) suggested the Be phenomenon will start to develop only in the second half of a B star’s MS lifetime, because of structural changes in the star. They noted that Be star-disk systems should start to appear in clusters 10 Myr old, corresponding to the midpoint MS lifetime of B0 stars, and their frequency should peak in clusters 13–25 Myr, corresponding to the midpoint MS lifetime of B1-B2 stars. The theoretical models of Meynet and Maeder (2000) and Maeder and Meynet (2001) indicate that the ratio of angular velocity to critical angular velocity steadily increases throughout the MS lifetime of early-type B stars. This might explain why the Be phenomenon is prevalent in the later part of a B star’s MS lifetime.
1.2.7 Role of metallicity in Be phenomenon

Feast (1972) found that about 50% of B stars in the Small Magellanic Cloud (SMC) cluster NGC 330 show Be phenomenon. This is quite a high fraction compared to 10–20% in Milky Way (Grebel et al., 1992). Maeder et al. (1999) suggested the influence of metallicity in Be star formation by indicating a higher fraction of Be stars in low-metallicity clusters (figure 1.3). In the magnitude interval $M_v = -5$ to $-1.4$ (O9–B3) they obtained a ratio $\text{Be}/(\text{B}+\text{Be}) = 0.11, 0.19, 0.23$ and $0.39$ for 21 clusters located in the interior of the Galaxy, the exterior of the Galaxy, the Large Magellanic Cloud (LMC) and SMC respectively. They have taken a mean metallicity value of $Z = 0.014$ for clusters towards center of Galaxy, $0.020$ in anti-center direction, $0.007$ in LMC and $0.002$ in SMC. Keller (2004) explored the role of metallicity in the $v\sin i$ value of B stars in field and young clusters of the LMC and Galaxy. He found that B-type stars in clusters rotate rapidly compared to the field counterparts. Moreover the average $v\sin i$ of B stars in the LMC clusters is found to be $146$ km/s while in the Galaxy, it is $116$ km/s. In low metallicity environments radiative winds are less efficient in B-type stars which result in the increment of rotation velocity rates, inorder to conserve angular momentum. This suggests the possibility of producing more Be stars in the Magellanic clouds since rapid rotation enhances the production of circumstellar disk in B-type stars.

Pamyatnykh (1999) showed that the $\beta$ Cephei and SPB instability strips vanish at $Z \leq 0.01$ and $Z \leq 0.006$ respectively. Hence it is expected to find less number of pulsators in LMC and no B-type pulsators in SMC. However Maeder and Meynet (2001) proposed the trigger of pulsation mechanism in rapid rotators through surface metal enrichment. Diago et al. (2009b) detected $\beta$ Cephei and SPB-type pulsators in low metallicity environments in contrast with the predictions of the current theoretical models. For Be stars, an increase in rotation at low metallicity can enhance non-radial pulsations or amplify the existing modes.
Martayan et al. (2006, 2007b) performed spectroscopic observations of B and Be stars in the LMC cluster NGC 2004 and the SMC cluster NGC 330 using VLT-GIRAFFE facility in MEDUSA mode. They found Be stars of similar age and mass rotate faster in the SMC than in the LMC, and are large compared to the Milky Way values (see Table 1.1). They postulated that Be stars begin their MS life with a high initial rotation velocity than B stars.

Figure 1.3: Relation between the number ratio Be/(B+Be) and the local metallicity for groups of clusters. The number counts were made in different magnitude intervals, the dots refer to counts made in the magnitude interval $M_v = -5, -1.4$, the crosses to the interval -5, -2 and the triangles to the interval -4, -2.

1.3 Multiwavelength studies of Be stars

Be stars are studied across the electromagnetic spectrum to understand Be phenomenon. The major studies in various bands are given below.
Table 1.1: The mean rotation velocities of Be stars in the SMC, LMC and Milky Way in various mass bins. For each sample, the mean age, mass, rotation velocity and the number of stars are given.

<table>
<thead>
<tr>
<th></th>
<th>age</th>
<th>$M/M_\odot$</th>
<th>$vsini$</th>
<th>N*</th>
<th>age</th>
<th>$M/M_\odot$</th>
<th>$vsini$</th>
<th>N*</th>
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<tbody>
<tr>
<td>SMC Be</td>
<td>8.0</td>
<td>3.7</td>
<td>277</td>
<td>14</td>
<td>7.6</td>
<td>7.6</td>
<td>297</td>
<td>81</td>
</tr>
<tr>
<td>LMC Be</td>
<td>8.1</td>
<td>4.4</td>
<td>241</td>
<td>18</td>
<td>7.5</td>
<td>7.7</td>
<td>285</td>
<td>21</td>
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<tr>
<td>MW Be</td>
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<td>10.8</td>
<td>335</td>
<td>13</td>
<td>7.2</td>
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<td>14</td>
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<td></td>
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<td>7.2</td>
<td>14.6</td>
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<td>6.8</td>
<td>14.9</td>
<td>278</td>
<td>17</td>
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</tbody>
</table>

1.3.1 Optical Photometry & Spectroscopy

The first comprehensive catalogue of Be stars is the Mount Wilson Catalogue (MWC) by Merrill and Burwell (1933, 1943, 1949, 1950) which contains 1600 Be, Ae stars and related objects. Photographic spectral atlas by Hubert-Delplace and Hubert (1979) contains spectra of 148 Be stars in the wavelength region 3800–6600 Å. A collection of high dispersion Hα and Feii line profiles of 77 Be stars were obtained by Hanuschik et al. (1996). An atlas of far ultra-violet (1200–3000 Å) and optical high resolution spectra of 166 Be stars have been given by Doazan et al. (1991). Andrillat et al. (1988, 1994) have done a spectral survey of 97 Be stars in the wavelength range 7500–8800 Å and 74 Be stars in the spectral range 9840–10200 Å. Bidelman (1976) had included Be supergiants and quasi-planetary nebulae into the class of Be stars. Later Jaschek et al. (1981) limited the discussion of Be stars as those which belong to the luminosity class III-V. Jaschek and Egret

Early work on emission line and shell spectra started as early as the 1920s and 30s by M. Wolf, O. Struve, A. H. Joy, L. B. Andrews, P. Swings and others. It was the pioneering work by Merrill (1949) who compiled several lists of stars with shell spectra that attracted the attention of observers. The field opened up by a comprehensive paper by Herbig in 1954 on NGC 2264 on the basis of spectroscopic data of e-stars. A systematic study of open clusters undertaken by Walker (1956, 1957, 1961) was the basis of subsequent research in this field; he included clusters such as NGC 2264, NGC 6530, NGC 6583, NGC 6611. The number of Be stars in open clusters has greatly increased in past years because of the search conducted by Schild and Romanishin (1976) in 29 northern clusters and by Lloyd Evans (1980) in NGC 3766 and IC 2581. Large surveys in the southern Milky way by Stephenson and Sanduleak (1977) and MacConnell (1981), and in the northern Milky way by the Vatican observers (Coyne et al., 1978) yielded an appreciable number of new Be stars in open clusters. Recently, McSwain and Gies (2005b) conducted a photometric survey of 55 southern open clusters and identified 52 definite Be stars and 129 probable candidates.

The photospheric absorption spectra of Be stars typically show broad absorption lines due to rotation, but are normal in terms of equivalent width (EW), ie. gravity, temperature and abundance (Slettebak, 1982). From an atlas of high-resolution (R = 50000), high signal to noise ratio H$_\alpha$ profiles of 24 bright southern Be stars, Hanuschik (1986) explained the inflections in the flanks of the profiles due to two-component structure. The inner broadened component is emitted at a radial distance of around 4 stellar radius while the outer component has an envelope boundary of 20 stellar radius. The inner component of H$_\alpha$ profile is broadened by Thomson scattering in addition to rotational and thermal broadening.
McLaughlin described three types of variability in the spectra of Be and shell stars:

(a) E/C variation, which is the change in the ratio of intensity of the emission lines with respect to continuum.

(b) V/R variation, which is the change in the ratio of the intensity of the violet to red component of double-peaked emission lines.

(c) appearance and disappearance of a shell-absorption spectrum, as seen in the case of Pleione (Gulliver, 1977).

The V/R variations on the timescale of years arise from velocity fields and non-axisymmetric density distributions in the circumstellar disk. The periodic component of this slow V/R variability can be understood by global one-armed oscillations (Okazaki, 1991; Hummel and Hanuschik, 1997).

Polarization in Be stars arises predominantly from Thomson scattering in the ionized, circumstellar material. From polarization measurements it is found that the optical radiation from Be stars is intrinsically polarized, which can be as high as 2%. This provides evidence for the disk like geometry of circumstellar envelope in Be stars (Coyne and McLean, 1982). Polarization strength may vary with emission strength and V/R ratio while the polarization angles are constant (Wood et al., 1997).

The disk geometry of the circumstellar envelope in Be stars is revealed through interferometric observations (Thom et al., 1986; Mourard et al., 1989; Stee et al., 1995; Quirrenbach et al., 1994). From the interferometric measurements of seven Be stars in H$_\alpha$, Quirrenbach et al. (1997) found that the H$_\alpha$ emission region extends up to 12 stellar radii, with a possible dependance on spectral type. From a correlated analysis of interferometric and spectropolarimetric observations, they derived a disk opening angle of around 20°. Wood et al. (1997) estimated a disk opening angle of 2.5° for ζ Tau from Be star models and on comparison with the observations of Quirrenbach et al. (1997). Tycner et al. (2005) found a relationship between the physical extent of H$_\alpha$ emitting region and net H$_\alpha$ luminosity from the...
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analysis of H\textalpha line profiles and interferometric observations. Interferometric studies have confirmed that the geometry of the circumstellar gas is disk-like and the estimates of opening angles point to a relatively thin disk.

1.3.1.1 Methods to detect Be stars in clusters

Objective-prism spectroscopy is the conventional technique used for detecting e-stars, in which a low dispersion prism (or a grating) is placed in front of the telescope objective and produces low resolution spectra in the focal surface, of all the objects in the field of view. The technique has been used for many years, mostly in conjunction with Schmidt telescopes. Grebel et al. (1992) surveyed clusters using Strömgren filters y, b and an H\textalpha filter of intermediate width. They used two-colour diagram (b−y) and (H\textalpha − y) to distinguish Be stars from B stars and bright supergiants. For the detection of Be stars in Magellanic cloud clusters like NGC 330, NGC 346, NGC 1818, NGC 1948, NGC 2004 and NGC 2100, Keller et al. (1999) used the difference between R band and narrow-band H\textalpha CCD images. McSwain and Gies (2005a) identified Be stars in open clusters using Strömgren b, y and narrowband H\textalpha photometry. They identified the B-type stars in the cluster using a theoretical isochrone fit to the (b−y, y) colour-magnitude diagram. This has been combined with (b−y, y−H\textalpha) colour-colour diagram to identify Be stars. Detection techniques used by various authors for individual clusters are discussed in next chapter.

We have used slitless spectroscopy to detect Be stars in young open clusters. The cluster region was observed with R band / Grism combination, which gives the dispersed image of stars in the field of view. By comparing with R band image, stars which show H\textalpha in emission are identified. The details of the setup and the techniques used will be explained in the next chapter.
1.3.2 Infra-red

The IR excess of Be stars is due to the presence of a large amount of circumstellar material with a relatively high density, since the emissivity for free-free radiation depends on the square of electron density ($n^2$). Gehrz et al. (1974) found a considerable excess with an energy distribution typical for free-free emission, i.e. an excess which increases with wavelength. Their data showed some evidence for a deviation in the energy distribution near 10$\mu$m (turnover point). Gehrz et al. (1974) interpreted the excess in terms of free-free emission from a circumstellar shell and derived a typical density for these shells as $10^{11}$ to $10^{12}$ cm$^{-3}$ for a representative set of Be stars and shell stars. For the physical conditions of Be envelope mentioned in Gehrz et al. (1974), the contributions from free-free and free-bound to the total nebular emission at 2.2 $\mu$m were found to be 63% and 37% respectively (Ashok et al., 1984). The flux from the central star in the wavelength region 15–20 $\mu$m is about 10–50 times fainter compared to the flux at 2 $\mu$m. The disk extension is a function of wavelength in IR region with 16 stellar radius ($R_*$) from 12, 25, 60 $\mu$m measurements (Waters, 1986), 8 $R_*$ from 2.3, 19.5 $\mu$m (Gehrz et al., 1974), 20 $R_*$ in near-IR (Dougherty et al., 1994) and 40 $R_*$ using Br$\gamma$ line (Stee and Bittar, 2001). The envelope size of $\alpha$ Ara (B3Ve) in N band has been estimated to be 14 $R_*$ from VLTI/MIDI observations (Chesneau et al., 2005). The schematic view of $\alpha$ Ara circumstellar environment used by the authors is given in figure 1.4.

Ashok et al. (1984) performed IR photometric studies of 55 northern Be stars in JHK broadbands and 15 in L band. The observed infrared continuum luminosity ($L_{IR}$) of the circumstellar envelope was found to exceed the energy input from the Lyman continuum luminosity ($L_L$). They also found a correlation between $L_{IR}$ and bolometric luminosity of the central star. Dachs and Wamsteker (1982)
performed broadband IR photometry in the JHKLM bands for 46 bright southern e-stars and N-band photometry for 8 of them. They found \((J - M)\) colour index strongly correlated with \(H_\alpha\) EW for Be stars earlier than B6. In the far IR, the observed spectral energy distribution index \(\alpha\), in the relation \(S_\nu \propto \nu^\alpha\), changes from \(\alpha = 0.6\) to \(\alpha > 1\) in the radio regime. This indicates some structural changes far away from the central star (Waters and Marlborough, 1994). Here \(\nu\) represents the frequency of the electromagnetic radiation.

1.3.3 Ultra-violet

Snow (1987) and Snow and Stalio (1987) used ultraviolet observations to discuss the phenomenon of super-ionization in Be stars. This refers to the presence of ionization stages higher than normally found in equilibrium at photospheric temperature. Be stars are found to be much more superionized than normal B-type stars since C IV and Si IV are observed in Be stars as late as B9 while they are only seen upto B2 and B5 respectively in normal B-type MS stars (Grady et al.,
1.3.4 X-ray & γ-ray

Quite a number of X-ray bright objects ($L_X \sim 10^{35} - 10^{38} \text{ ergs/s}$) belong to the class of X-ray binaries in which a neutron star or a black hole forms a binary system with a companion star. In High Mass X-ray binaries (HMXB), mass is accreted ($10^{-11} - 10^{-8} \text{ M}_\odot/\text{yr}$) from the donor star (OB supergiant or Be star) onto the compact object. X-ray binary pulsars are neutron star HMXBs which emit pulsed X-rays (Sasaki et al., 2003). The mechanism of X-ray outburst occur when a neutron star, which is in wide and eccentric orbit, passes close to the circumstellar disk of a Be star (Apparao, 1985; Okazaki and Negueruela, 2001). This binary system is of astrophysical interest since it is possible to determine the mass and radius of the Be star, the mass of the neutron star, an estimate of stellar wind intensity, mass transfer mechanisms and evolutionary history from optical and X-ray observations (Rappaport and van den Heuvel, 1982). The Be/X-ray binary system constitutes 60–70\% of the population of HMXBs in Milky Way and the LMC while it is more than 90\% in the SMC (Haberl and Sasaki, 2000).

Gamma-ray (γ-ray) binaries are HMXBs that exhibit very high energy emission in the MeV-TeV range. The following candidates are identified as part of VHE observations, whose companion is reported to be a Be star. PSR B1259-63/SS 2883 is a binary system of a 48 ms pulsar in orbit around a B2e companion star (Johnston et al., 1992). Aharonian et al. (2005) reported the discovery of very-high energy γ-ray emission ($\sim$ TeV) from this system. The Be/X-ray binary LS I +61 303 is one of the brightest known γ-ray sources, detected by COS B (Hermsen et al., 1977; Albert et al., 2008). The Be companion is of B0Ve spectral type and
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is in a highly eccentric orbit with a period of 26.5 days (Grundstrom et al., 2007). HESS J0632+057 is a γ-ray binary identified in HESS survey and the follow-up observation with XMM-Newton identified it as a massive star MWC 148 of spectral type B0pe (Hinton et al., 2009).

1.4 Outline of the Thesis

We have done a survey to search for e-stars in northern open clusters, belonging to different parts of the Galactic disk. Compared to field CBe stars, cluster candidates offer precise values of distance, reddening and chemical composition, which helps to understand their evolutionary state better. We used slitless spectroscopy to find e-stars in clusters, which is an innovative concept for a survey of this magnitude. The medium resolution spectra of identified e-stars are taken and the spectral parameters like EW and rotation velocity have been used to understand the properties of disk and angular momentum evolution. The sample of 157 stars in 42 clusters has been used to derive conclusion about the role of environment and mechanisms for the formation of Be stars. From photometric and spectroscopic studies, we propose a bimodal distribution in Be star population. The early subtype (B0–B2) evolve to become Be stars while others (B2–A0) are born in Be phase. The detailed description of the studies summarized in each chapter is given below.

1.4.1 Chapter 1

In Chapter 1, we have given an introduction to Be stars. We have explained Be phenomenon in CBe stars and the efforts underway to resolve the puzzle. Rapid rotation, stellar wind, non-radial pulsation, magnetic field and binary interaction
are the proposed mechanisms to resolve Be phenomenon in Be stars. We have explored the theoretical aspects of each of these mechanisms with the observational developments in each front. Be stars are studied in various bands in the electromagnetic spectrum, to understand the nature of the star with the formation and evolution of circumstellar disk. A quick glance on prominent studies in optical, IR, UV, X-ray and $\gamma$-ray are presented.

1.4.2 Chapter 2

The details of the survey to search for e-stars in 207 young open clusters using slitless spectroscopy are explained in this chapter. We found 157 e-stars in 42 open clusters, most of which are aged less than 100 Myr. The properties of these e-stars are discussed in the context of the clusters which harbour them. The youngest clusters to have CBe stars are IC 1590, NGC 637 and NGC 1624 (all 4 Myr old) while NGC 6756 (125 – 150 Myr) is the oldest cluster to have CBe stars. A detailed description of the studies conducted in each of these 42 clusters is given in this chapter. The optical $V$ vs $(B-V)$ colour magnitude diagram (CMD) with near infra-red $(J-H)$ vs $(H-K_s)$ colour-colour diagram (near-IR CCDm) are used to classify CBe stars from HAeBe stars in terms of near-IR excess. The spectra of the e-stars along with the line details are given.

1.4.3 Chapter 3

The statistical analysis of the collective sample of 157 e-stars are presented in this chapter. The optical photometric data are taken from the references listed in WEBDA (http://www.univie.ac.at/webda/navigation.html) while near-IR data are taken from 2MASS (http://vizier.u-strasbg.fr/cgi-bin/VizieR?-source=II/246). We have explored the role of evolution in Be phenomenon by locating the position
of Be stars in optical CMD, which was explained in previous chapter. The CBe stars are located all along the MS in the optical CMDs of clusters of all ages, which indicates that the Be phenomenon is unlikely only due to core contraction near the turn-off. The spectral type shows a bimodal distribution, peaking in B1–B2 and B6–B7 spectral bins. Rich clusters like NGC 7419, NGC 2345, NGC 663 and h & χ Persei are found to favour the formation of early-type Be stars. Most of the identified e-stars are CBe candidates (145 stars, 92%), while some are Herbig Be (HBe; 10, 6%) and Herbig Ae (HAe; 2, 2%) candidates. Our survey is more or less complete in the northern sky and it covers various star forming regions in the Galaxy like Perseus, Monoceros and Cygnus. Most of the surveyed clusters were found to have Be star fraction (N(Be)/N(B+Be)) to be less than 10%, which agrees with previous studies. We propose two mechanisms responsible for CBe phenomenon. The first mechanism is where some stars are born CBe stars, which may happen for spectral types later than B1. The second mechanism is where the B stars evolve to CBe stars, likely due to evolution, enhancement of rotation or structural changes at the end of the MS. This is likely to happen in early B spectral types.

1.4.4 Chapter 4

From the spectroscopic survey of 152 CBe stars, various spectral and evolutionary properties of stars and their disk are studied. Apart from the Balmer lines in emission, spectra of most of the stars show FeII, Paschen and OI lines in emission while HeI is seen in absorption. The Balmer decrement ($D_{34}$) of Be stars is found to show bimodal distribution with peak values of 2.5 and 3.9, unlike the typical nebular value of 2.7. Majority of surveyed stars (76%) may have optically thick disks, identified by the presence of large $D_{34}$, high H$_{α}$ EW, metallic lines and high ($H-K_s$)$_0$ values. We found Lyman $β$ fluorescence as the mechanism for the pro-
duction of 8446 Å line in 24% of the surveyed stars and 47% show line formation (O\textsc{i} 8446 Å & 7772 Å lines) due to collisional excitation. The rotation velocity of candidate stars is found to be in the range 150–300 km/s, which matches with the values of field CBe stars. The rotation velocity of the disks were found to range between 50–250 km/s, thus the circumstellar disk is found to lag behind the star by 50–100 km/s. The angular momentum evolution of stars and disk as a function of age and spectral type suggest bimodal origin of Be stars. Our results suggest that stars in the B0–B2 spectral bin are found to spin up towards the end of their MS life time, which is 10–20 Myr. Stars in the B0–B4 bin show enhanced H\textsubscript{α} emission at the end of their MS lifetime, as inferred from the enhancements observed at 12.5 and 25 Myr. All the above results indicate that the activity in early type Be stars gets accelerated towards the end of the MS evolution. Thus early type stars evolve to become Be stars. Similar variation in properties were not found for stars in the later spectral types (B4–A0), suggesting that the Be phenomenon differs in early and late type stars.

1.4.5 Chapter 5

HAeBe and CBe stars are e-stars in different evolutionary phases. The nature and formation of circumstellar disk in these stars are different. As explained in Chapter 3, we found that 8 percent of the surveyed e-stars belongs to HAeBe category. In this chapter we have identified sure candidates from optical and near-IR photometry, Spectral Energy Distribution (SED) and spectroscopy. We found 3 HBe and 2 HAe candidates from a sample of 157 e-stars. The age of these HAeBe stars, estimated using PMS isochrones, were found to range between 0.25 - 3 Myr. We combined the optical and near-IR photometry to estimate the duration of star formation in the clusters, Bochum 6, IC 1590, NGC 6823 and NGC 7380. We found ongoing star formation in all these clusters, with an appreciable number of
PMS stars. All the four clusters were found to be forming stars for the last 10 Myr.

1.4.6 Chapter 6

Summary of this thesis study is presented here along with the future plans.