Unveiling the Physical Conditions in NGC 6910

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Received 2020 February 7; revised 2020 April 3; accepted 2020 April 15; published 2020 June 10

Abstract

Deep and wide-field optical photometric observations along with multiwavelength archival data sets have been employed to study the physical properties of the cluster NGC 6910. The study also examines the impact of massive stars on their environment. The age, distance, and reddening of the cluster are estimated to be \( \sim 4.5 \) Myr, \( 1.72 \pm 0.08 \) kpc, and \( E(B - V)_{\text{min}} = 0.95 \) mag, respectively. The mass function slope \( (\Gamma = -0.74 \pm 0.15) \) in the cluster region is found to be flatter than the Salpeter value \( (\sim -1.35) \), indicating the presence of an excess number of massive stars. The cluster also shows mass segregation toward the central region due to their formation processes. The distribution of warm dust emission is investigated toward the central region of the cluster, showing the signature of the impact of massive stars within the cluster region. Radio continuum clumps powered by massive B-type stars \( (\text{age range} \sim 0.07-0.12 \) Myr) are traced that are located away from the center of the stellar cluster NGC 6910 \( (\text{age} \sim 4.5 \) Myr). Based on the values of different pressure components exerted by massive stars, the photoionized gas associated with the cluster is found to be the dominant feedback mechanism in the cluster. Overall, the massive stars in the cluster might have triggered the birth of young, massive B-type stars in the cluster. This argument is supported with evidence of the observed age gradient between the cluster and the powering sources of the radio clumps.

Unified Astronomy Thesaurus concepts: Open star clusters (1160); Star formation (1569); Initial mass function (796); Luminosity function (942)

Supporting material: machine-readable table

1. Introduction

Massive stars \( (>8 M_\odot) \) are regarded as powerful agents that can significantly affect their host molecular cloud through their photoionized gas and/or stellar winds. The impact of energetic feedback from massive stars can trigger a new generation of young protostars. However, understanding the feedback mechanism of massive OB stars is still under debate (Zinnecker & Yorke 2007; Tan et al. 2014). In this context, young open clusters \( (\text{age}<10 \) Myr) are thought to be a unique laboratory for understanding the processes of star formation, as they harbor both low-mass and high-mass stars of very young ages. Young open clusters, just formed from the gravitationally bound molecular clouds and still embedded in the parent nebulos regions, contain dust and gas. The study of the ionized gas, dust \( (\text{cold and warm}) \) emission, and molecular gas can give us observational clues about the physical processes that govern their formation (Bastian et al. 2010; Deharveng et al. 2015).

Furthermore, the investigation of young open clusters offers the opportunity to study the initial mass function (IMF) of stellar objects, which is an important statistical tool to understand the formation of stars (Jose et al. 2017; Sharma et al. 2017; Panwar et al. 2018, and references therein). It is supported by the fact that young open clusters host a broad mass range of cluster members, which can also be used to quantify the relative numbers of stars in different mass bins and to constrain the IMF.

A few examples exist in the literature (see, e.g., Pandey 2001; Pandey et al. 2005; Sharma et al. 2007, 2008; Jose et al. 2017) showing change in the slope of the mass function (MF) as a function of radial distance from the cluster center in the sense that the central region has a greater number of massive stars as compared to the outer regions. Hence, in cases of young clusters, it indicates the imprint of the star formation process, while in old clusters, it may be due to dynamical evolution of the clusters. Massive systems sink toward the center, allowing them to gain more potential energy, which heats the cluster. The timescale for this mass segregation to complete is not very well known. It is considered as an active area of research, especially because of the need to understand trapezium-like subsystems in star clusters (Mermilliod 2000) and the associated implications for the formation mechanisms of massive stars (Bonnell et al. 1998).

Therefore, with the aim of investigating the stellar IMF, as well as the physical processes governing the interaction and feedback effect of massive stars in their own vicinity, we have selected the promising young cluster NGC 6910. This cluster is believed to host at least 10 massive stars of spectral type B2V–O9V \( (\text{e.g., Reipurth & Schneider 2008}) \). However, the rich population of massive stars in this cluster and their effects on the surrounding field are largely unexplored and deserve a systematic study. To the best of our knowledge, no comprehensive observational investigation of a large-scale area around NGC 6910 is available in the literature. In order to compute the age and distance of the cluster, in this paper, we present new deep, wide-field, and multiband \( (UBV(RI)_c) \) photometry around NGC 6910. Furthermore, we have also examined the distribution of massive stars, ionized gas, and warm dust emission in the cluster using multiwavelength data sets.
The structure of the paper is as follows. In Section 2, a brief overview of this region is presented. Section 3 provides details of new optical observations and reduction procedures along with the available data sets from various archives. In Section 4, we study the structure of this cluster. In this section, we also discuss the basic parameters of the cluster (i.e., reddening law, extinction, distance) and the derived MF slope in the region and explore the physical environment around the cluster, including feedback effects from the massive stars. Finally, Section 5 summarizes the various results.

2. Overview of the NGC 6910 Cluster

The NGC 6910 cluster was discovered in 1786 by William Herschel, and many photometric studies of the cluster members have been presented since then (for details, see Reipurth & Schneider 2008). The distance to NGC 6910 amounts to about 1.5 kpc (Davies & Tovmassian 1963; Becker & Fenkart 1971; Battinelli & Capuzzo-Dolcetta 1991; Dambis 1999), placing it behind the Cygnus Rift, within the Local (Orion) spiral arm of the Galaxy. In consequence, the average color excess of the cluster members, $E(B-V)$, is found to be of the order of 1 mag and varies across the cluster (Turner 1976). The age of the cluster was estimated to be in the range between 5 and 10 Myr (Davies & Tovmassian 1963; Harris 1976; Battinelli & Capuzzo-Dolcetta 1991; Delgado & Alfaro 2000).

The NGC 6910 cluster is part of a complex of actively star-forming molecular clouds and young clusters, the Cygnus X region, which is extended over an $\sim 7^\circ \times 7^\circ$ area and located at a distance of about 1.7 kpc (Reipurth & Schneider 2008). Several OB stars in Cygnus X were grouped into nine OB associations by Humphreys (1978), and the famous Cyg OB2 association is the most massive among them; it contains several thousand OB stars and is analogous to the young globular clusters in the Large Magellanic Cloud (Reddish et al. 1966; Massey & Thompson 1991). The OB associations in the Cygnus X region are among the largest groups of O-type stars known in our Galaxy and can strongly influence their entire surrounding field. In Figure 1, we show the color composite of the $4^\circ \times 4^\circ$ field of view (FOV) of the Cygnus X region containing NGC 6910 (black box) obtained by using a 1.4 GHz Canadian Galactic Plane Survey (CGPS) image, 12 $\mu$m Wide-field Infrared Survey Explorer (WISE) image, and 115 GHz image (Dame et al. 2001). The approximate locations of OB associations are also shown as white ellipses (see Humphreys 1978; Schneider et al. 2006, 2007).

The IC 1318 b/c regions are part of a single giant H II region, prominent in the radio domain (Baars & Wendker 1981) and bifurcated by the massive, highly structured dust lane L889 (Dickel et al. 1977; Wendker et al. 1983). A possible ionizing source of the IC 1318 b/c nebula is an O9V-type star known as GSC 03156–00657 (Arkhipova & Lozinskaia 1978; Appenzeller & Wendker 1980). However, this star is not a member of NGC 6910 because it is located away from the cluster center. The precise relation between the NGC 6910 cluster and the H II region is unclear. Also, this cluster has been known to contain at least 40 stars showing H$\alpha$ in emission, around 12 pre-main-sequence (PMS) stars, and 10 massive stars (Mel'kian & Shevchenko 1990; Shevchenko et al. 1991; Delgado & Alfaro 2000; Kubát et al. 2007; Reipurth & Schneider 2008), which makes it an ideal site to investigate star formation activities.

3. Observation and Data Reduction

3.1. Optical Data

The optical CCD $UBV(RI)$ photometric data of the NGC 6910 region, centered at $\alpha_{2000} = 20^h 23^m 12^s$, $\delta_{2000} = +40^\circ 46^\prime 42^\prime\prime$, $I = 78.683$, and $b^2 = 2.013$, were acquired by using the 2048 $\times$ 2048 pixel$^2$ CCD camera mounted on the f/13 Cassegrain focus of the 104 cm Sampurnanand telescope of the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India. In this setup, each pixel of the CCD corresponds to $0^\prime\prime.37$, and the entire chip covers a FOV of $\sim 13 \times 13$ arcmin$^2$ on the sky. We have carried out observations of this cluster in four pointings covering a total FOV of $22 \times 23$ arcmin$^2$, as shown in Figure 2. To improve the signal-to-noise ratio (S/N), the observations were carried out in the binning mode of $2 \times 2$ pixels. The readout noise and gain of the CCD are 5.3 e$^-$ and 10 e$^-$ ADU$^{-1}$, respectively. The average FWHMs of the star images were $\sim 3^\prime\prime$. A number of
bias and twilight-flat frames were also taken during the observations. A number of short- and deep- (long-) exposure frames were taken to observe both bright and faint stars in the field. The complete log of the observations is given in Table 1.

The CCD data frames were reduced by using the computing facilities available at the Center of Advanced Study, Department of Physics, Kumaun University, and ARIES, both located in Nainital, India. Initial processing of the data frames was done by using the IRAF5 and ESO-MIDAS6 data reduction packages. Photometry of the cleaned frames was carried out by using the DAOPHOT-II software (Stetson 1987). The point-spread function was obtained for each frame by using several isolated stars. Magnitudes obtained from different frames were averaged. When brighter stars were saturated on deep-exposure frames, their magnitudes were taken from short-exposure frames. We used the DAOGROW program (Stetson 1990) for construction of an aperture growth curve required for determining the difference between the aperture and profile-fitting magnitudes. Calibration of the instrumental magnitudes to the standard system was done by using the procedures outlined by Stetson (1992). The broadband $UBV(RI)$, observations of the NGC 6910 region were standardized by observing stars in the SA98 field (Landolt 1992) centered at $\alpha_{2000} = 06^h52^m12^s$, $\delta_{2000} = -00^\circ19'17''$. The calibration equations derived by using least-squares linear regression are as follows:

$$u = U + (6.771 \pm 0.003)$$
$$- (0.009 \pm 0.002)(U - B) + (0.677 \pm 0.005)X,$$

$$b = B + (4.548 \pm 0.002)$$
$$+ (0.008 \pm 0.001)(B - V) + (0.407 \pm 0.003)X,$$

$$v = V + (4.149 \pm 0.002)$$
$$- (0.046 \pm 0.002)(V - I_c) + (0.256 \pm 0.003)X,$$

$$r_c = R_c + (4.046 \pm 0.002)$$
$$- (0.013 \pm 0.001)(V - R_c) + (0.190 \pm 0.003)X,$$

$$i_c = I_c(4.559 \pm 0.004)$$
$$- (0.017 \pm 0.001)(V - I_c) + (0.135 \pm 0.006)X,$$

where $U$, $B$, $V$, $R_c$, and $I_c$ are the standard magnitudes; $u$, $b$, $v$, $r_c$, and $i_c$ are the instrumental aperture magnitudes normalized per second of exposure time; and $X$ is the airmass.

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5 IRAF is distributed by the National Optical Astronomy Observatories, USA.
6 ESO-MIDAS is developed and maintained by the European Southern Observatory.

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**Figure 2.** Color-composite image obtained by using the 22 $\mu$m (red; WISE), 2.2 $\mu$m (green; 2MASS), and 0.55 $\mu$m (blue; present study) images for an area of $\sim22 \times 23$ arcmin$^2$ around the NGC 6910 cluster. Red contours are the surface density contours, whereas the green circle shows the cluster boundary (see Section 4.1.1). The white diamond is the location of the massive O9.5 star (BD+40 4148) reported in this region (Reipurth & Schneider 2008).

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**Table 1**

Log of Optical Observations with the 104 cm Sampurnanand Telescope, Nainital

| Date of Observations/Filter | Exp. (s) x No. of Frames |
|----------------------------|--------------------------|
| 2005 Nov 4                  |                          |
| $U$                        | 180 x 1, 300 x 9          |
| $B$                        | 120 x 3, 180 x 8          |
| $V$                        | 60 x 8, 120 x 3           |
| $R_c$                      | 30 x 9, 60 x 3            |
| $I_c$                      | 30 x 10, 60 x 2           |
| NGC 6910 (center)          |                          |
| $U$                        | 60 x 3, 300 x 3           |
| $B$                        | 30 x 3, 180 x 3           |
| $V$                        | 60 x 3, 120 x 3           |
| $R_c$                      | 10 x 3, 60 x 3            |
| $I_c$                      | 10 x 3, 60 x 3            |
| NGC 6910 (center)          |                          |
| 2005 Jun 13                |                          |
| $U$                        | 300 x 3, 1200 x 3         |
| $B$                        | 300 x 3, 900 x 3          |
| $V$                        | 10 x 3, 60 x 3, 900 x 3   |
| $I_c$                      | 10 x 1, 300 x 4           |
| NGC 6910 (F2)              |                          |
| 2006 Sep 28                |                          |
| $U$                        | 300 x 4, 1200 x 3         |
| $B$                        | 60 x 3, 900 x 3           |
| $V$                        | 10 x 1, 60 x 3, 900 x 3   |
| $I_c$                      | 10 x 3, 300 x 4           |
| NGC 6910 (F3)              |                          |
| 2005 Jun 15                |                          |
| $U$                        | 60 x 1, 300 x 3, 1200 x 3 |
| $B$                        | 10 x 3, 60 x 3, 900 x 3   |
| $V$                        | 30 x 3, 60 x 1, 900 x 3   |
| $I_c$                      | 10 x 3, 20 x 1, 60 x 1, 300 x 4 |
| NGC 6910 (F4)              |                          |
| 2006 Sep 26                |                          |
| $U$                        | 300 x 3                   |
| $B$                        | 120 x 4                   |
| $V$                        | 120 x 3                   |
| $I_c$                      | 10 x 3, 30 x 1, 300 x 4   |
| NGC 6910 (F4)              |                          |
| 2006 Sep 27                |                          |
| $U$                        | 300 x 3, 1200 x 3         |
| $B$                        | 60 x 3, 900 x 3           |
| $V$                        | 60 x 3, 900 x 3           |
In the cluster field, we have generated secondary standards by applying the above equations to the stars that were observed in the same night as the standard field. Then, we calibrated all of the stars in different subregions of the cluster field that were observed during different nights by applying the offset between the instrumental and standard magnitudes of the secondary standards. We have carried out a comparison of the present calibrated data with those CCD data (V < 17 mag) present in the literature, i.e., Delgado & Alfaro (2000; UBV) and Kolaczkowski et al. (2004; VI). The difference \( \Delta \) (present – literature) as a function of present \( V \) magnitudes and \( B - V \) colors is shown in the left panel of Figure 3. Although there is some trend in the difference of \( V \) mag and \( V - I_c \) colors in the range of 11–16 mag in the \( V \) band, the scatter is small, and the effect will be minimal for the scientific results of this study. The comparison indicates that the magnitudes and colors obtained in the present work are in fair agreement with those available in the literature. The typical DAOPHOT errors in different bands as a function of \( V \) magnitudes are shown in the right panel of Figure 3. It can be seen that the errors become large (>0.1 mag) for fainter magnitudes and were not used in the present analysis. In this study, a total of 4638 sources have been identified with detections at least in the \( V \) and \( I_c \) bands and having photometric errors less than 0.1 mag up to \( V \approx 22 \) mag.

The above optical photometry, which will be further used for our analysis, can be incomplete due to various reasons, e.g., nebulosity, crowding of the stars, detection limit, etc. In particular, it is very important to know the completeness limits in terms of mass to derive correct MF slopes. The IRAF routine ADDSTAR of DAOPHOT-II was used to determine the completeness factor (CF). In this method, artificial stars of known magnitudes and positions are randomly added in the original frames, and then these artificially generated frames are rereduced by the same procedure as used in the original reduction. The ratio of the number of stars recovered to those added in each magnitude gives the CF as a function of magnitude. We followed the procedure given by Sagar & Richtler (1991). We added artificial stars to both the \( V \) and \( I \) images in such a way that they have similar locations geometrically but differ in \( I \) brightness according to the mean \((V - I)\) colors of the main-sequence (MS) stars. The luminosity distribution of artificial stars is such that more stars are inserted at fainter magnitude bins. A number of independent sets of artificial stars are inserted into a given data frame for the determination of the CF. In all, about 15% of the total stars are added so that the crowding characteristics of the original frame do not change significantly (see Sagar & Richtler 1991). The minimum value of the CF in the \( V \) and \( I \) bands is used to correct the data incompleteness (see Sagar & Richtler 1991). The CFs for different regions of the NGC 6910 cluster are shown in Figure 4. As expected, we found that the incompleteness of the data increases with increasing magnitude and stellar density (i.e., toward the core of the cluster; see Section 4.1.1). In this study, our data in the cluster region are found to be 80% complete up to 20.6 mag in the \( V \) band, corresponding to a mass completeness limit of 0.8 \( M_\odot \) for an observed distance of 1.72 kpc and \( E(B - V) = 0.95 \) mag (see Section 4.1.4).

### 3.2. Archival Data Sets

We have also used the archival near-infrared (NIR), mid-infrared (MIR), and radio data of the selected region as observed in optical bands for our analysis. A brief description of these is given in Table 2. The processed Herschel
temperature and column density \((N(H_2))\) maps (resolution \(\sim 12''\)) have been utilized in this work and were downloaded from the publicly available site.\(^7\) These maps were generated as a part of the EU-funded ViaLactea project (Molinari et al. 2010). The Bayesian Point Process MAPping procedure (Marsh et al. 2015) was adopted for producing these Herschel maps (see also Marsh et al. 2017).

4. Results and Discussion

4.1. The Cluster’s Physical Properties

4.1.1. Extent and Structure of the Cluster

The initial stellar distribution in star clusters may be governed by the structure of the parental molecular cloud and also how star formation proceeds in the cloud. Later evolution of the cluster may be governed by the internal gravitational interaction among member stars and external tidal forces due to the Galactic disk or giant molecular clouds (Chen et al. 2004; Sharma et al. 2006). The structure and radius of the NGC 6910 cluster (core and corona regions) can be studied by means of density estimations. Since the distribution of stars in a cluster follows a systematic distribution from the cluster to the field region, the center of the cluster is estimated by involving a Gaussian kernel with the stellar distribution and taking the point of maximum density as the center. This was performed for both axes to get the center coordinates of the cluster, i.e., \(\alpha_{2000} = 20^h 23^m 18^s, \delta_{2000} = +40^\circ 46' 12''\). To determine the radial stellar surface density, the cluster was divided into a number of concentric rings. The projected radial stellar density in each concentric circle was obtained by dividing the number of stars in each annulus by its area, and this is plotted in Figure 5 for various magnitude levels. The error bars are derived assuming that the number of stars in each annulus follows Poisson statistics. The point where the radial density becomes nearly constant and merges with the contaminating field star density (indicated by horizontal dashed lines in the plot) is defined as the radius of the cluster, \(r_{\text{cl}}\) (see also Sharma et al. 2006). For almost all magnitude levels, we can determine the \(r_{\text{cl}}\) of this cluster as 5′/5. The observed radial density profile (RDP) of the cluster was parameterized following the approach by Kaluzny & Udalski (1992), in which the projected radial density \(\rho(r)\) is described as

\[
\rho(r) \propto \frac{f_0}{1 + \left(\frac{r}{r_c}\right)^2},
\]

where the cluster’s core radius, \(r_c\), is the radial distance at which the value of the projected radial density, \(\rho(r)\), becomes half of the central density, \(f_0\). Within the uncertainties, the King model (King 1962) well reproduces the RDP of the cluster at different magnitude levels, except for \(V < 21\) mag. This might be due to the apparent contamination in the cluster region from the field stars at fainter magnitudes. By fitting the King model surface density profile to the observed RDP of stars with \(V \approx 19\) mag having a least-fitting error, we have found that the core radius of this cluster comes out as 1′/4.

To further study the structure of the cluster and stellar density distribution in the region, we generated stellar surface density maps using the nearest-neighbor method as described by Gutermuth et al. (2005). We have taken the radial distance necessary to encompass the 20th-nearest star detected in the optical band (\(V < 16\) mag) and computed the local surface density in a grid size of \(\sim 20''\). Surface density contours in the NGC 6910 region are shown in Figure 2 as red contours, whereas the cluster region as determined by RDP is shown as a green circle. The lowest contour is 1σ above the mean of the stellar density (i.e., 1.3 + 2.2 stars pc\(^{-2}\) at 1720 pc), and the step size is equal to 1σ (2.2 stars pc\(^{-2}\) at 1720 pc). Figure 2 reveals that stellar surface density contours correspond to the cluster size (5′/5) determined by the RDP. The core region of this cluster seems to be elongated.

4.1.2. Cluster Membership of Stellar Sources

Membership determination based on proper-motion (PM) studies will be useful to carry out astrophysical studies in the region of the cluster. To determine the membership probability, we adopted the method described in Balaguer-Núñez et al. (1998) by using Gaia PM data (see Table 2). This method was previously used for \(\omega\) Centauri (Bellini et al. 2009), NGC 6809 (Sariya et al. 2012), NGC 6366 (Sariya & Yadav 2015), and NGC 3201 (Sariya et al. 2017). In Figure 6 (left panel), we show the PM \(\mu_x, \cos(\delta)\) and \(\mu_\delta\) vector point diagrams (VPDs; top panels) and the corresponding \(G\) versus \((G_{BP} - G_{RP})\) color–magnitude diagrams (CMDs; bottom panels) for the stars located within the radius of the cluster, i.e., \(r_{\text{cl}} < 5'\). The left subpanel shows all stars, while the middle and right subpanels show the probable cluster members and field stars, respectively. A tight circular clump can be seen visually at \(r_{\text{cl}} < 3.4\), \(\mu_x = -5.4\) mas yr\(^{-1}\) having a radius of 0.8 mas yr\(^{-1}\) in the top left subpanel of Figure 6. As we know that the cluster stars have more or less similar PMs, this group most probably represents the PMs of cluster stars. The chosen radius is a compromise between losing cluster members with poor PMs and including field stars sharing the cluster mean PM. The corresponding well-defined CMD of these most probable cluster members can be seen in the bottom middle subpanel. The remaining stars in the VPD are assigned as field stars, which is further demonstrated by the broad distribution in their CMD (bottom right subpanel). Few cluster members might be visible in this CMD because of their wrong estimation of PMs due to large errors in their values. Assuming a distance of 1.74 kpc (Delgado & Alfaro 2000) and a radial velocity

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\(^7\) http://www.astro.cardiff.ac.uk/research/ViaLactea/
The dispersion of 1 km s$^{-1}$ for open clusters (Girard et al. 1989), the expected dispersion ($\sigma_r$) in PMs would be $\sim$0.12 mas yr$^{-1}$. For the remaining field stars, we have calculated $\mu_{xd}=-2.2$, $\sigma_{xd}=3.9$ mas yr$^{-1}$ and $\mu_{yd}=-4.6$, $\sigma_{yd}=4.3$ mas yr$^{-1}$ as the mean and standard deviation of their PM values in the R.A. and decl. axes, respectively. These values are further used to construct the frequency distributions of cluster stars ($\phi_x$) and field stars ($\phi_f$) by using the equations given in Yadav et al. (2013) and then the value of membership probability (ratio of distribution of cluster stars with all stars) by using the following equation:

$$P_\mu(i) = \frac{n_e \times \phi_x(i)}{n_e \times \phi_x(i) + n_f \times \phi_f(i)},$$

where $n_e=(0.16)$ and $n_f=(0.84)$ are the normalized numbers of stars for the cluster and field region ($n_e + n_f = 1$).

The estimated membership probability of the Gaia sources located within the radius of the NGC 6910 cluster region is plotted as a function of $G$ magnitude in Figure 6 (right panel). As can be seen in this plot, a high membership probability ($P_\mu > 80\%$) extends down to $G \sim 20$ mag. At fainter magnitudes, the probability gradually decreases. In Figure 6 (right panel), we have also plotted the parallax of the same stars as a function of $G$ magnitude. Except for a few outliers, most of the stars with high membership probability ($P_\mu > 80\%$ and $G < 20$ mag) are following a tight distribution. Finally, from the above analysis, we calculate the membership probability of 916 stars in the NGC 6910 cluster region, and 128 stars were assigned as cluster members based on their high membership probability ($P_\mu > 80\%$ and $G < 20$ mag). The details of these cluster members are given in Table 3.

4.1.3. Reddening Law in the Region

The nature of the diffuse interstellar medium (ISM) is often characterized by the ratio of total-to-selective extinction, represented by $R_V = A_V/E(B-V)$. The normal reddening law for the solar vicinity gives the value $R_V = 3.1 \pm 0.2$ (Guetter & Vrba 1989; Whittet 2003; Lim et al. 2011), but in the case of several star-forming regions having an unusual distribution of dust sizes, it is found to be abruptly high (see, e.g., Pandey et al. 2000, Pandey et al. 2008; Hur et al. 2012; Pandey et al. 2013; Kumar et al. 2014). To separate the influence of normal extinction produced by the general ISM from that of abnormal extinction arising within regions, we used $(V-\lambda)$ versus $(B-V)$ two-color diagrams (TCDs; see Chini et al. 1990; Pandey et al. 2000, 2003), where $\lambda$ indicates one of the wavelengths of the broadband filters ($J, H, K, L_c$). Figure 7 shows the $(V-\lambda)$ versus $(B-V)$ TCDs of all cluster member stars having optical and NIR observations. The slopes of the least-squares fit to the distribution of stars in the $(V-I_c), (V-J), (V-H), (V-K)$ versus $(B-V)$ TCDs are found to be 1.35 ± 0.10, 2.33 ± 0.12, 2.94 ± 0.11, and 3.10 ± 0.09, respectively, which are higher by a factor of $m \sim 1.21 \pm 0.01$ than those found for the general ISM (1.10, 1.96, 2.42, and 2.60; see Pandey et al. 2003). This concedes a higher value for $R_V (>3.75 \pm 0.02$; please refer Pandey et al. 2003 for a detailed description of reddening law estimation), indicating larger grain sizes of the material in this region as compared to the general ISM. We have also calculated the $R_V$ value for the stars that are not cluster members (i.e., $P_\mu < 20\%$ and $V < 20$ mag) and found a similar value of $R_V (>3.75 \pm 0.02$) as for cluster member stars. This means that, in general, the $R_V$ value is higher in this region. Inside dense dark clouds, the coagulation due to grain collision and accretion of ice mantles on grains can change the size distribution leading to higher $R_V$ values (Cardelli et al. 1989). In many star-forming regions, $R_V$ values tend to diverge

| Survey | Wavelength(s) | Resolution | References |
|--------|--------------|------------|------------|
| Two Micron All Sky Survey (2MASS) | 1.25–2.2 $\mu$m | $\sim$2.5 | Skrutskie et al. (2006) |
| UKIRT NIR Galactic Plane Survey (GPS) | 1.25–2.22 $\mu$m | $\sim$0.78 | Lawrence et al. (2007) |
| Spitzer Enhanced Imaging Products | 3.6, 4.5, 5.8, and 8 $\mu$m | $\sim$2" , $\sim$2", $\sim$2", $\sim$2" | * |
| WISE | 3.4, 4.6, 12, and 22 $\mu$m | $\sim$6"1, $\sim$6"4, $\sim$6"5, $\sim$12" | Wright et al. (2010) |
| Spitzer MIPS Inner Galactic Plane Survey | 24 $\mu$m | $\sim$6" | Carey et al. (2005) |
| Herschel Infrared Galactic Plane Survey | 70, 160, 250, 350, and 500 $\mu$m | $\sim$5"8, $\sim$12", $\sim$18", $\sim$25", $\sim$37" | Molinari et al. (2010) |
| Planck polarization data | 850 $\mu$m | $\sim$294" | Planck Collaboration et al. (2014) |
| CO survey archive | 2.6 mm | $\sim$8'4 | Dame et al. (2001) |
| NVSS | 21 cm | $\sim$46" | Condon et al. (1998) |
| CGPS | 21 and 74 cm | 1' x 1' cscδ, 3/4 x 3/4 cscδ | Taylor et al. (2003) |
| Gaia DR2 (magnitudes, parallax, and PM) | 330–1050 nm | 0.4 mas | Gaia Collaboration et al. (2018b, 2018a) |

Note.

* https://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/overview.html.

Figure 5. The RDPs of the NGC 6910 cluster at different magnitude levels using the present optical data. The solid curve shows a least-squares fit of the King (1962) profile to the observed data points. The error bars represent 1/$\sqrt{N}$ errors. The horizontal line indicates the density of the field stars.
from the normal value toward the higher ones; for example, $R_V = 3.7$ (Kumar et al. 2014; the Carina region), 3.3 (Pandey et al. 2013; NGC 1931), 3.5 (Sharma et al. 2012; NGC 281), and 3.7 (Pandey et al. 2008; Be 59).

4.1.4. Extinction, Distance, and Age of the Cluster

The extinction toward the cluster NGC 6910 can be estimated by using the $(U - B)$ versus $(B - V)$ TCD, as shown in Figure 8 (left panel). In this figure, stars inside the cluster region ($r_{cl} < 5.5’$; black dots), along with the intrinsic zero-age main sequence (ZAMS; blue dotted curve) taken from Pecaut & Mamajek (2013), are shown. We have also overplotted the probable cluster member stars identified by using the PM data (see Section 4.1.2) as red circles. The distribution of the stars shows a large spread along the reddening vector, indicating heavy differential reddening in this region. It reveals two different populations, one (mostly black dots) distributed along the ZAMS and another (mostly red circles) showing a large spread in reddening value. The former, having negligible reddening, must be the foreground population, and the latter could be member stars. If we look at the MIR images of this region (Figure 1), we see several dust lanes, along with enhancements of nebular emission at many places. Both of them are likely responsible for the large spread of reddening in the NGC 6910 region. The ZAMS is shifted along the reddening vector with a slope of $E(U - B)/E(B - V) = 0.72 \times 1.21$ (corresponding to $R_V \sim 3.75$; see Section 4.1.3) to match the distribution of stars showing minimum reddening among the member population. Only those stars were chosen for reddening analysis if their position in the TCD indicated that their spectral type is A or earlier. This choice was dictated by several factors, such as metallicity, distribution of binary stars, rotation, PMS stars, and error in photometry (for more details, see Golay 1974; Phelps & Janes 1994). The cluster foreground reddening value, $E(B - V)_{\text{min}}$, thus comes out to be $\sim 0.95$ mag, and the ZAMS reddened by this amount is shown by a red solid curve. The other stars may be embedded in the nebulosity of this region, and the maximum reddening value, $E(B - V)_{\text{max}}$, for them comes out to be 1.35 mag (red dashed curve). The approximate error in the reddening measurement $E(B - V)$ is $\sim 0.1$ mag and has been determined by the procedure outlined in Phelps & Janes (1994).

The photometric distance ($\sim 1.5$ kpc) of this cluster has been estimated previously in the literature (Shevchenko et al. 1991; Vansevicius 1992). Recent distance estimates put this cluster at a distance of 1.6 (Kolaczkowski et al. 2004) to 1.74 (Delgado & Alfonso 2000) kpc. Delgado & Alfonso (2000) quoted the distance and age of this cluster as 1740 pc and 6.8 Myr, respectively. However, as the extinction in the NGC 6910 region is high and apparently anomalous, these distance measurements will be sensitive to the adopted $R_V$ values. We calculated the distance of the member stars of this cluster by using their parallax values with good accuracy (error $< 0.05$ mas) from Bailer-Jones et al. (2018). The mean distance value comes out to be $1.72 \pm 0.08$ kpc. The distance and age of a cluster can also be derived quite accurately by using the CMD of their MS member stars (see Phelps & Janes 1994; Sharma et al. 2006; Friel et al. 2014; Perren et al. 2015; Sharma et al. 2017; Bossini et al. 2019; Pandey et al. 2020a, 2020b). The $V$ versus $(V - I)$ CMD for stars lying within the cluster region is shown in the right panel of Figure 8. The probable cluster member stars (see Section 4.1.2) are also plotted in the figure with red circles. Here also, the CMD reveals two different populations, one (mostly black dots) for foreground stars having almost zero reddening value (near the dotted curve) and another (mostly red circles) for the cluster members at higher
| ID | $\alpha_{2000}$ (deg) | $\delta_{2000}$ (deg) | $V$ (mag) | $B$ (mag) | $I$ (mag) | $R$ (mag) | $U$ (mag) | Parallax (mas) | $\mu_{\alpha}\cos(\delta)$ (mas yr$^{-1}$) | $\mu_{\delta}$ (mas yr$^{-1}$) | $G$ (mag) | $(G_{BP} - G_{RP})$ (mag) | $P_{mi}$ (%) |
|----|-----------------|-----------------|--------|--------|--------|--------|--------|--------------|------------------|------------------|--------|----------------------|----------|
| 1  | 305.888133      | 40.693244       | 18.376 ± 0.011 | 19.838 ± 0.015 | 16.211 ± 0.010 | ...   | ...   | 0.753 ± 0.131 | −2.706 ± 0.148 | −5.341 ± 0.197  | 17.450 | 2.080                 | 98       |
| 2  | 305.898745      | 40.707285       | 19.526 ± 0.014 | 21.124 ± 0.033 | 17.243 ± 0.010 | ...   | ...   | 0.374 ± 0.216 | −2.408 ± 0.225 | −5.536 ± 0.323  | 18.504 | 2.145                 | 96       |
| 3  | 305.875944      | 40.712293       | 19.277 ± 0.013 | 20.818 ± 0.023 | 16.937 ± 0.013 | ...   | ...   | 0.453 ± 0.161 | −2.974 ± 0.183 | −5.727 ± 0.247  | 18.245 | 2.167                 | 81       |
| 4  | 305.797771      | 40.716103       | 19.653 ± 0.013 | 21.479 ± 0.052 | 17.105 ± 0.060 | 18.307 ± 0.027 | ...   | 0.389 ± 0.205 | −2.527 ± 0.306 | −5.285 ± 0.314  | 18.427 | 2.377                 | 96       |

(This table is available in its entirety in machine-readable form.)
reddening values and larger distances. The CMD of cluster members displays a few MS stars up to $V = 16$ mag and PMS stars at the fainter end. The blue dotted curve in the right panel of Figure 8 denotes a ZAMS from Pecaut & Mamajek (2013), randomly corrected for a distance of 0.8 kpc, matching well with the distribution of foreground stars. We have further visually fitted the post-MS isochrone for an age of 4.5 Myr from Pastorelli et al. (2019) to the lower envelope of the distribution of member stars where the bend occurs in the MS. This choice of visual fitting was imposed by several factors, such as distribution of binary stars, rotation, and evolutionary effects (for details, see Golay 1974; Phelps & Janes 1994). The isochrone, when corrected for extinction, is matching nicely to the lower envelope of the MS stars. The locations of massive stars such as HD 194279 (B2Ia C, blue supergiant; Adelman & Yüce 2007), BD+40 4148 (O9.5V; Hoag & Applequist 1965),

Figure 7. Shown are the $(V - I)$, $(V - J)$, $(V - H)$, and $(V - K)$ vs. $(B - V)$ TCDs for the stellar sources associated with the NGC 6910 region (black dots; $P_\mu > 80\%$ and $G < 20$ mag). Straight lines show the least-squares fit to the distribution of stars.

Figure 8. Left panel: $(U - B)$ vs. $(B - V)$ TCD for all optically detected sources in the NGC 6910 region ($\theta < 5.5\arcmin$). Red open circles are cluster member stars identified by their PM data. The dotted blue curve represents the intrinsic ZAMS for $Z = 0.02$ by Pecaut & Mamajek (2013). The solid and dashed red curves represent the ZAMS shifted along the reddening vector for $E(B - V) = 0.95$ and 1.35 mag, respectively. Right panel: $V$ vs. $(V - I)$ CMD for similar sources. The ZAMS (Pecaut & Mamajek 2013; blue dotted curve corrected for a distance of 0.8 kpc) and post-MS isochrone for 4.5 Myr (Pastorelli et al. 2019; solid red curve corrected for a distance of 1.72 kpc and reddening $E(B - V) = 0.95$ mag) are also shown.
BD +40 4146 (B1 D; Walker & Hodge 1968), and LS III +40 12 (B0.5V; Comerón & Pasquali 2012) are also matching well with the isochrone. Therefore, from both parallax and CMD analyses, we have derived the distance and post-MS age of this cluster as 1.72 kpc and 4.5 Myr, respectively. The approximate error in the age estimation is $\sim 2.5$ Myr, as has been determined by the procedure outlined in Phelps & Janes (1994). A summary of the physical parameters of the cluster is given in Table 4.

### 4.1.5. MF and Dynamical Age of the Cluster

The distribution of stellar masses that form in one star formation event in a given volume of space is called IMF, and together with star formation rate, it is one of the important statistical tools to study star formation. The MF is often expressed by a power law, $N(\log m) \propto m^\Gamma$, and the slope of the MF is given as

$$\Gamma = d \log N(\log m) / d \log m,$$

(8)

where $N(\log m)$ is the number of stars per unit logarithmic mass interval. We have used our deep optical data to generate the MF of different regions of the NGC 6910 cluster as it reaches to the fainter end as compared to the Gaia DR2 data. For this, we have utilized the optical CMDs of the sources in the target region and that of the nearby field region of equal area, decontaminated the former sources from foreground/background stars, and corrected for data incompleteness using a statistical subtraction method already described in detail in our previous papers (see Sharma et al. 2007; Pandey et al. 2008; Chauhan et al. 2011; Sharma et al. 2012; Pandey et al. 2013; Jose et al. 2013; Sharma et al. 2017).

As an example, in Figure 9 (top left panel), we show $V$ versus $(V - I_c)$ CMDs for the stars lying within the cluster region in subpanel (a) and for those in the reference field region (taken as an annular area outside the cluster region having radius 5.5 $\leq r_{\text{field}} < 7.65$) in subpanel (b). In subpanel (c), we plot the statistically cleaned $V$ versus $(V - I_c)$ CMD for the cluster region that is showing the presence of PMS stars. Since, at the age of 4.5 Myr, the stars having $V \leq 16$ mag are considered to be still on the MS, for these stars, the luminosity function was converted into MF using theoretical models by Pastorelli et al. (2019). The MF for the PMS stars was obtained by dividing the number of stars in various mass bins (shown as evolutionary tracks) having ages $\leq 7$ Myr (age of cluster, i.e., 4.5 Myr + error in age) in Figure 9, subpanel (c). The resulting MFs of the cluster region using MS $(2.3 < M/M_\odot < 24.86)$ and MS+PMS $(0.8 < M/M_\odot < 24.86)$ stars are plotted in Figure 9 (top right) in the top and bottom subpanels, respectively. Similarly, we have also derived MF slopes $\Gamma$ for the core and corona regions of the cluster using both MS and MS+PMS stars, and their values are given in Table 5.

As the NGC 6910 cluster region contains several massive stars, we shall study the environmental effects due to the presence of high-mass stars on the lower-mass end of the present-day MF. In Figure 9 (top right panel), we can observe that the MF for the cluster region shows a turnover at $1.58 M_\odot$, and the distribution up to this mass limit can be represented by a single power law. The MF slopes of different regions of the cluster NGC 6910 are generally shallower than the Salpeter value $-1.35$, which indicates the abundance of massive stars in this cluster. It has been shown (see, e.g., Scalo 1986, 1998; Kroupa 2002; Chabrier 2003; Corbelli et al. 2005) that, for masses above $\sim 1 M_\odot$, the MF can generally be approximated by a declining power law with a slope similar to that found by Salpeter (1955). To investigate further, we look for the signature of mass segregation in this cluster by checking the change of MF slope from the core region to the outer corona region of this cluster, which is in fact getting steeper in the outer corona region. To evaluate the degree of mass segregation in the cluster, we subdivided the samples of cluster stars into two mass groups and plotted their cumulative distribution with respect to radial distance from the cluster center as shown in Figure 9 (bottom panels) for both MS (left) and MS+PMS (right) stars. Figure 9 (bottom panels) also reveals the effect of mass segregation in the sense that relatively massive stars tend to lie near the cluster center. The Kolmogorov–Smirnov test confirms the abovementioned mass segregation at a confidence level better than $\sim 99\%$.

Dynamical relaxation is one of the possible reasons for the segregation of massive stars in the central region of this cluster. At the time of formation, the cluster may have a uniform spatial stellar mass distribution; however, the spatial stellar mass distribution would change with time as the cluster evolves dynamically. Low-mass stars in a cluster may possess high random velocities because of dynamical relaxation; consequently, they will try to occupy a larger volume than the high-mass stars and move away from the cluster center (Mathieu 1985; McNamara & Sekiguchi 1986). To check whether mass segregation is primordial or due to dynamical relaxation, we have estimated the dynamical relaxation time, $T_E$, the time in which individual stars exchange sufficient energy so that their velocity distribution approaches that of a Maxwellian equilibrium. The dynamical relaxation time is given by

$$T_E = \frac{8.9 \times 10^{5}N^{1/2}R_h^{3/2}}{m^{1/2}\log(0.4N)},$$

(9)

where $N = 215$ is the number of cluster members, $R_h = 1.6$ pc is the radius containing half of the cluster mass, and $m = 4.31 M_\odot$ is the average mass of the cluster stars (Spitzer & Hart 1971). The total number of MS stars and the total mass of MS stars $(775 M_\odot)$ in the given mass range are obtained with the help of the MF. This total mass of MS stars should be considered as a lower limit to the total mass of the cluster. The
half-mass–radius $R_h$ as half of the cluster radius appears to be a tenable approximation. We used half of the cluster radius ($r_{cl}$) obtained from the optical data as the half-mass–radius. The dynamical age of this cluster comes out to be 6.5 Myr, which is more than the age of this cluster (i.e., 4.5 Myr), suggesting that the dynamics is not fully responsible for the observed mass segregation, and it may be the imprint of the star formation process itself.

Table 5
The MF Slope for Two Subregions and the Whole Cluster Region in the Given Mass Range

| Mass Range ($M_\odot$) | MF Slopes ($\Gamma$) |
|------------------------|----------------------|
|                        | Core Region | Corona Region | Cluster Region |
| 24.86 $-$ 0.8          | $-0.42 \pm 0.20$    | $-0.69 \pm 0.14$ | $-0.74 \pm 0.15$ |
| 24.86 $-$ 2.3          | $-0.38 \pm 0.39$    | $-0.54 \pm 0.28$ | $-0.58 \pm 0.25$ |
4.2. Physical Environment around the Cluster

4.2.1. Multiwavelength Picture of the Region

Recently available high-resolution radio/infrared/submillimeter observations have helped us to probe deeply embedded star-forming regions and provided a wealth of new information to probe young stars, gas and dust distribution, ionized gas distribution, etc., which are very good indicators/tools for star formation studies (e.g., Deharveng et al. 2010; Watson et al. 2010; Dewangan et al. 2016, 2017).

In Figures 10(a) and (b), the large-scale environment of the cluster NGC 6910 is shown using the CGPS 480 and 1420 MHz continuum images, respectively. These radio continuum images reveal an extended spherical-like structure, which is related to the γ Cygni SNR. Our selected target area is highlighted by a white box in both of the radio continuum images, indicating the location of the NGC 6910 cluster at the border of the SNR. Uchiyama et al. (2002) reported the age of SNR G78.2+2.1 to be 6600 yr. No molecular $^{13}$CO emission is observed toward the NGC 6910 cluster (see positions at $l = 78^\circ69$, $b = 1^\circ96$ in Figure 8 in Piano et al. 2019). It is likely that the SNR might have influenced its surrounding environment. However, the impact of the young SNR G78.2+2.1 on the formation of the relatively old cluster NGC 6910 (∼4.5 Myr; Section 4.1.4) is unlikely. Figure 10(c) displays the NRAO VLA Sky Survey (NVSS) 1.4 GHz continuum map. The NVSS map indicates the presence of the extended diffuse radio continuum emission ($1\sigma \sim 0.45 \text{ mJy beam}^{-1}$) showing the existence of radio continuum clumps toward the cluster, which is not seen in the CGPS continuum images having lower sensitivity (see the white box in Figures 10(a)–(c)). The presence of the radio clumps suggests the existence of embedded massive OB stars, implying the ongoing massive star formation in the region. Using the Planck image at 850 μm (or 353 GHz), a tracer of the cold dust emission, we show a field hosting the SNR and the cluster NGC 6910 in Figure 10(d). It seems that the cluster area is not associated with any noticeable cold dust emission.

Figures 11(a) and (b) present the Spitzer 24 μm and Herschel 70 μm images of the area selected in this paper, respectively. Both infrared images are overlaid with the NVSS 1.4 GHz continuum emission contours. The extension of the stellar cluster is also marked in both infrared images. The images at 24 and 70 μm allow one to qualitatively trace the warm dust
emission present in the cluster NGC 6910. In Figures 11(c)–(f), we present a zoomed-in view of the central part of the cluster (see the dashed boxed in Figure 7(b)) using the 3.6, 8.0, 24, and 70 μm images, respectively. These images are also overlaid with the NVSS 1.4 GHz radio continuum emission contours. Diffuse emission is seen in all of these infrared images except...
We find that the warm dust emission depicted in the 24 and 70 μm images is surrounded by the Spitzer 8.0 μm emission. Note that the Spitzer band at 8.0 μm hosts PAH features at 7.7 and 8.6 μm. Considering the inclusion of PAH features in the 8.0 μm band, the existence of PDRs is evident in the NGC 6910 region, suggesting the impact of massive OB stars present in the stellar cluster.

Figure 12(a) shows the submillimeter image at 350 μm (see the white box in Figure 10(a)). A filled hexagon indicates the position of the massive star BD+40 4148 (spectral class = O9.5V; Hoag & Applequist 1965). (b) Overlay of the stellar surface density contours (in red) and the NVSS 1.4 GHz radio continuum emission contours (in black) on the feature traced in the Spitzer 24 μm image (i.e., filled area). The NVSS contours (in black) are shown with levels... of 11.5, 13, 15, 17, 22, and 25 mJy beam⁻¹, where 1σ ∼ 0.45 mJy beam⁻¹. A filled area traced in the Spitzer 24 μm image is shown with a contour of 58 MJy sr⁻¹. The lowest stellar surface density contour (in red) is 1σ (i.e., 2.2 stars pc⁻² at 1720 pc), and the step size is equal to 1σ. Arrows highlight the NVSS radio peaks observed toward the cluster. (c) Overlay of the 1.4 GHz NVSS radio continuum contours (in pink) on the Herschel temperature map. (d) Overlay of the 1.4 GHz NVSS radio continuum contours (in pink) on the Herschel column density (N(H₂)) map. In panels (c) and (d), the radio emission contours are the same as in Figure 11(a), and the broken contour (in black) indicates the dust temperature (T_d) at 17.5 K. In all panels, a star represents the central position of the stellar cluster, and an extension of the cluster is indicated by a big circle.

Figure 12(a) shows the submillimeter image at 350 μm (resolution ∼25″), where the extension of the stellar cluster is also marked. In the east direction of the cluster, the submillimeter emission is observed and is not spatially coincident with the 24 and 70 μm emission (see Figures 11(a) and (b)). In Figure 12(b), we plot the stellar surface density contours against the distribution of the warm dust emission and ionized emission in the cluster area. In Figure 12(b), the warm dust emission is traced using the Spitzer 24 μm image (see filled area), while the NVSS 1.4 GHz continuum emission depicts the ionized emission (see black contours). We find that the radio continuum peaks (ionized clumps or H II regions) are located away from the center of the cluster (see arrows in Figure 12(b)). Based on the analysis of the NVSS radio continuum data, we calculate that these ionized clumps are powered by B1V–B0.5V stars (see Table 2 in Panagia 1973, for a theoretical value), and their dynamical ages are estimated to be ∼0.07–0.12 Myr. In this calculation, we have employed the same procedures as carried out in Dewangan et al. (2017). Using the integrated radio continuum flux density and radius (R_{H II}) of each ionized clump, the number of Lyman continuum photons (N_{LyC}) was estimated following the equation given in Matsakis et al. (1976). Then, with knowledge of the N_{LyC} and R_{H II} values, the age of each ionized clump or H II region has been estimated using the equation given in Dyson & Williams (1980).
The Herschel temperature and column density maps can be used to deduce the physical conditions present in a given star-forming region (see Dewangan 2019; Dewangan et al. 2019a, 2019b). Figures 12(c) and (d) show the Herschel temperature and column density maps (resolution ~12″), respectively. These Herschel maps are also overlaid with the NVSS radio continuum emission contours. In Figure 12(c), we have traced a feature in the temperature map using a contour of $T_d = 17.5$ K (≈average dust temperature). Using a black broken contour, this feature is also highlighted in both Herschel maps. The ionized clumps distributed within the cluster are associated with emission at $T_d = 17.5–18.0$ K. In Figure 12(d), we do not find high column density materials in the direction of the cluster except in the east direction, where radio peaks are seen harboring the very young stellar sources.

4.2.2. The Star Formation Scenario

Our careful analysis of various observational data sets suggests that the MF slope of the cluster region is shallower than the Salpeter value (i.e., $\Gamma = -1.35$). It shows a signature of the presence of more massive stars compared to the low-mass stars in the cluster region. This argument suggests the effect of mass segregation. A comparison between the cluster age (i.e., $\sim 4.5$ Myr) and its dynamical relaxation time (i.e., $\sim 6.5$ Myr) indicates that the cluster is not relaxed yet. Furthermore, the observed mass segregation seen in this cluster may be the imprint of their formation processes. These properties make the NGC 6910 cluster a special target to study the feedback effect of massive star(s) on its environment.

Massive stars can provide positive feedback affecting star formation by accumulating neutral material at the periphery of H II regions via the “collect-and-collapse” mechanism (Elmegreen & Lada 1977; Whitworth et al. 1994) or by the compression of preexisting dense condensations via the “radiation-driven implosion” (RDI) mechanism (Bertoldi 1989; Lefloch & Lazareff 1994). Star formation induced in a region by these processes is also called “triggered” star formation, and observational signposts usually include the age sequence of the stellar sources and the distribution of cool, warm, and ionized gas in the region (see also Samal et al. 2007; Sharma et al. 2007; Jose et al. 2011; Sharma et al. 2012, Sharma et al. 2017). Observational studies of bubbles associated with H II regions created by massive stars suggest that their expansion probably triggers 14%–30% of star formation in our Galaxy (e.g., Deharveng et al. 2010; Kendrew et al. 2012; Thompson et al. 2012), thus implying the importance of massive OB stars on the star formation activities in our Galaxy.

The cluster NGC 6910 contains several massive OB stars, and the most massive of them is an O9.5V star known as BD +40 4148 (Hoag & Applequist 1965). The position of this massive star is marked by a diamond in Figure 2. In general, a massive star can influence its surroundings through its different feedback pressure components (such as pressure of an H II region ($P_{\text{HII}}$), radiation pressure ($P_{\text{rad}}$), and stellar wind ram pressure ($P_{\text{wind}}$); see, e.g., Bressert et al. 2012; Dewangan et al. 2017). These pressure components can be expressed as (see, e.g., Bressert et al. 2012)

$$P_{\text{HII}} = \mu m_\text{H} c^2 \left( \frac{3 N_\text{Ly}}{4 \pi a \rho \sigma T_d^4} \right).$$

$$P_{\text{rad}} = L_{\text{bol}} / 4 \pi c D_f^2,$$

and

$$P_{\text{wind}} = M_w V_w / 4 \pi D_f^2.$$ (12)

In the equations above, $N_{\text{Ly}}$ is the number of Lyman continuum photons, $c$ is the speed of light in the photoionized region ($= 11$ km s$^{-1}$; Bissab et al. 2009), $\sigma_P$ is the radiative recombination coefficient ($= 2.6 \times 10^{-13} / (10^4 K/T_d)^{0.7}$ cm$^3$ s$^{-1}$; Kwan 1997), $\mu$ is the mean molecular weight in the ionized gas ($= 0.678$; Bissab et al. 2009), $m_\text{H}$ is the hydrogen atom mass, $M_w$ is the mass-loss rate, $V_w$ is the wind velocity of the ionizing source, $L_{\text{bol}}$ is the bolometric luminosity of the ionizing source, and $D_f$ is the projected distance from the location of the O9.5V-type star to the ionized clumps, which is adopted to be 1.0 pc (see Figure 12(b)).

We have used $L_{\text{bol}} = 66,070 L_\odot$ (Panagia 1973), $M_w \approx 1.58 \times 10^{-9} M_\odot$ yr$^{-1}$ (Marcolino et al. 2009), $V_w \approx 1500$ km s$^{-1}$ (Marcolino et al. 2009), and $N_{\text{Ly}} = 1.2 \times 10^{48}$ photons per second (Panagia 1973) for a star of O9.5V spectral type to estimate different pressure components, which come out to be $P_{\text{HII}} \approx 2.6 \times 10^{-10}$, $P_{\text{rad}} \approx 7.1 \times 10^{-11}$, and $P_{\text{wind}} \approx 1.3 \times 10^{-13}$ dyne cm$^{-2}$. It gives the total pressure (i.e., $P_{\text{total}} = P_{\text{HII}} + P_{\text{rad}} + P_{\text{wind}}$) driven by a massive star as $\sim 3.4 \times 10^{-10}$ dyne cm$^{-2}$. It appears that the $P_{\text{HII}}$ component is relatively higher than other two pressure components. Furthermore, we find that the value of $P_{\text{total}}$ is higher than the pressure of a typical cool molecular cloud ($P_{\text{MC}} \sim 10^{-11}–10^{-12}$ dyne cm$^{-2}$ for a temperature $\sim 20$ K and particle density $\sim 10^{10}$ cm$^{-3}$; see Table 7.3 of Dyson & Williams 1980). It suggests that the massive star seems to have significantly influenced its environment. Additionally, the photoionized gas associated with the cluster appears to be responsible for the feedback mechanism.

We also find the existence of young ionized clumps, located along the edge of the NGC 6910 cluster containing massive stars, in a high column density region. The center of the cluster is associated with warm dust emission, and the ionized clumps are distributed in the PDRs. Hence, it is likely that these massive stars might have influenced the birth of the youngest massive B-type stars (age range $\sim 0.07–0.12$ Myr) powering the ionized clumps. In the triggered star-forming region Sh 2-294, Samal et al. (2007) also found ionized clumps away from the exciting source. We did not find any ring/arc of gas and dust surrounding the NGC 6910 cluster, as has been found in the regions showing the collect-and-collapse mechanism (for details, see Deharveng et al. 2005). Therefore, the age difference between the young B-type stars and the central massive star (O9.5V), and the distribution of PDRs/warm and cold gas and dust/ionized gas in the region, indicate that the star formation at the border of NGC 6910 is maybe due to the RDI process. However, with the currently available observations and data, it is too early to establish or rule out either of the scenarios.

5. Summary and Conclusions

We have performed deep multiband (UBV(RI),) and wide-field optical photometric observations (FOV $\sim 22 \times 23$ arcmin$^2$) around the NGC 6910 cluster up to 22 mag in the V band. The data are complete down to 20.6 mag in the V band, corresponding to the mass completeness of 0.8 $M_\odot$. The optical data, along with multiwavelength archival data, have been used
to study the ongoing physical processes in the cluster NGC 6910. The main results are summarized as follows.

1. By using the RDP of stellar sources, we estimated the cluster radius as 5′.5 with a core radius of 1′.4. We have used the stellar surface density contours to study the structure of this cluster and found that the stellar surface density contours match with the cluster size determined by the RDP. The core region of this cluster seems to be elongated.

2. We have calculated the membership probability for 916 stars in the cluster NGC 6910 and found 128 member stars with membership probabilities higher than 80% with \( G < 20 \) mag. We have calculated a distance to the cluster as 1.72 \( \pm 0.08 \) kpc using a parallax for cluster members. With the help of TCDs and CMDs, we have also estimated the foreground reddening \( E(B-V)_{\text{min}} \), distance, and age of the cluster NGC 6910 to be 0.95 mag, 1.72 kpc, and 4.5 Myr, respectively.

3. It is found that the MF slope \( \Gamma \) in the cluster region (i.e., \( -0.74 \pm 0.15 \)) is shallower than the Salpeter value (i.e., \( -1.35 \)), which indicates the presence of a large number of massive stars as compared to low-mass stars in the cluster region and an effect of mass segregation. A contrast between the cluster age (i.e., \( \sim4.5 \) Myr) and its dynamical relaxation time (i.e., \( \sim6.5 \) Myr) suggests that the cluster is not relaxed yet, and the observed mass segregation seen in this cluster may be the imprint of the formation process.

4. The distribution of warm dust is found in the central region of the cluster, which also contains massive stars. The cluster is surrounded by PDRs along with the presence of radio peaks (ionized clumps) and cold gas. The total pressure (i.e., \( P_{\text{total}} = \sim3.4 \times 10^{-15} \) dyne cm\(^{-2} \)) driven by the massive O9.5V star (BD+40 4148) at the location of the ionized clumps is also found to be very high as compared to the pressure of a typical cool molecular cloud. All of these signatures strongly suggest the influence of massive star(s) of the NGC 6910 cluster on its environment.

5. We have determined the spectral type and age of the young star responsible for the radio emission near the border of the cluster (ionized clumps) as B-type and \( \sim0.07–0.12 \) Myr, respectively. The age gradient between the central massive star (4.5 Myr) and the ionized clumps (\( \sim0.07–0.12 \) Myr), along with other signatures, indicates the influence of massive star(s). This suggests that the feedback effects from the central massive stars are triggering the formation of the next generation of stars in the surrounding region.

We thank the anonymous reviewer for a critical reading of the manuscript and constructive suggestions that greatly improved the overall quality of the paper. The observations reported in this paper were obtained using the 1 m Sampurnanand Telescope, Nainital, India. This work is based on data obtained as part of the UKIRT Infrared Deep Sky Survey (UKIDSS). This publication made use of data products from 2MASS (a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and NSF) and archival data obtained with the Spitzer Space Telescope (operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA). This study has made use of data from the European Space Agency (ESA) mission Gaia (https://cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by the institutions participating in the Gaia Multilateral Agreement. D.K.O. acknowledges the support of the Department of Atomic Energy, Government of India, under project No. 12-R&D-TFR-5.02-0200. L.K.D. acknowledges the support of the Department of Space, Government of India.

Software: ESO-MIDAS (Banne et al. 1992), IRAF (Tody 1986, 1993), DAOPHOT-II software (Stetson 1987).

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