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Rising and Falling Motions of Gas above the Perseus Arm

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Summary. Rising and falling motions of neutral hydrogen (H I) gas above the Perseus arm are studied in detail on the basis of systematic variation of radial velocity of the H I gas with galactic latitudes. We find that the gas is ejected out of the arm for duration of about 3×10^7 years with an initial speed of about 70 km/s in the z-direction. After reaching its maximum height of $z\approx2$ kpc, the gas falls freely toward the galactic plane.
The rising H I gases have a spatial correlation with H II regions and OB-clusters. An enhancement in the background radio emission is found above the Perseus arm ($l=100°$–$140°$) in coincidence with the region where the rising gas is observed. The rising motion is considered to be driven by an inflation of magnetic field due to enhanced cosmic ray pressure in and around this region.

Key words: the Galaxy — neutral hydrogen — Perseus arm — high z-extension — galactic halo

I. Introduction

Vertical high z-extension of interstellar gas from the galactic plane has been observed by some authors (Münch and Zirin, 1961; Kepner, 1970; Verschuur, 1973a–c; Heiles, 1973). Kepner (1970) and Verschuur (1973b) have given some evidences for existence of H I (neutral hydrogen) spiral arms high away from the galactic plane: the Perseus and outer arms can be traced up to height of $z=1$–3 kpc. These gases high above the galactic plane cannot be in hydrostatic equilibrium because insufficient random motion is observed, so that the gravitational force sweeps them back to the plane within 5×10^7 years. Hence the presence of such a high z-extension of gases poses a new problem on the dynamics and structure of the Galaxy and of the spiral arm.
Recently Tosa and Sofue (1974: Paper I) have proposed a model that the gases observed high above the spiral arm are supplied by ejection out of the spiral arm. This paper presents a detailed description of the model of the z-motion of the gas above the spiral arm with special reference to the Perseus arm ($l=80$–$170°$). We discuss the dynamics of the vertically ejected gas clouds in Section II. Discussions are made of the spatial correlation of the gases in rising and falling phases with early type objects such as OB-clusters, O-associations, and/or H II regions (Section III), searching for a mechanism to give rise to the z-motion of the gas. We study also the distribution of background emission of radio continuum over the Perseus region and its connection with the rising H I gases (Section IV). Results reported in Paper I are somewhat refined.

II. Motion of Gas Clouds Ejected out of the Perseus Arm

In Paper I, we have obtained latitude-radial velocity diagrams ($b-v$ diagram) for gas clouds above the Perseus arm on the basis of a model for ejection of gas clouds out of the arm. The results have shown a good fit to the observed ($b-v$) diagrams by Kepner (1970). As in Paper I, we assume that the gas clouds are thrown up in the z-direction from an "active region" fixed to the gaseous disk and they rise up, attain their maximum height and fall freely under the gravitational force due to the Galaxy.
If we neglect the drag force due to the ambient gas in the galactic halo, the vertical velocity v_z is calculated by applying the energy conservation as follows;

$$\frac{1}{2}v_e^2-\frac{1}{2}v_z^2=-\int_0^z K(z)\,dz\,, \qquad (1)$$

where v_e is the ejection velocity of the cloud, and $K(z)$ the gravitational acceleration in the z-direction. The acceleration $K(z)$ above the Perseus arm is evaluated using values given by Oort (1960) and Innanen (1966). The maximum height Z is related to the ejection velocity v_e as

$$\frac{1}{2}v_e^2=-\int_0^Z K(z)\,dz\,. \qquad (2)$$

The time t elapsed from the ejection, or the age of the ejected gas cloud is given by

$$t=\int_0^z\frac{dz}{v_z}\,. \qquad (3)$$

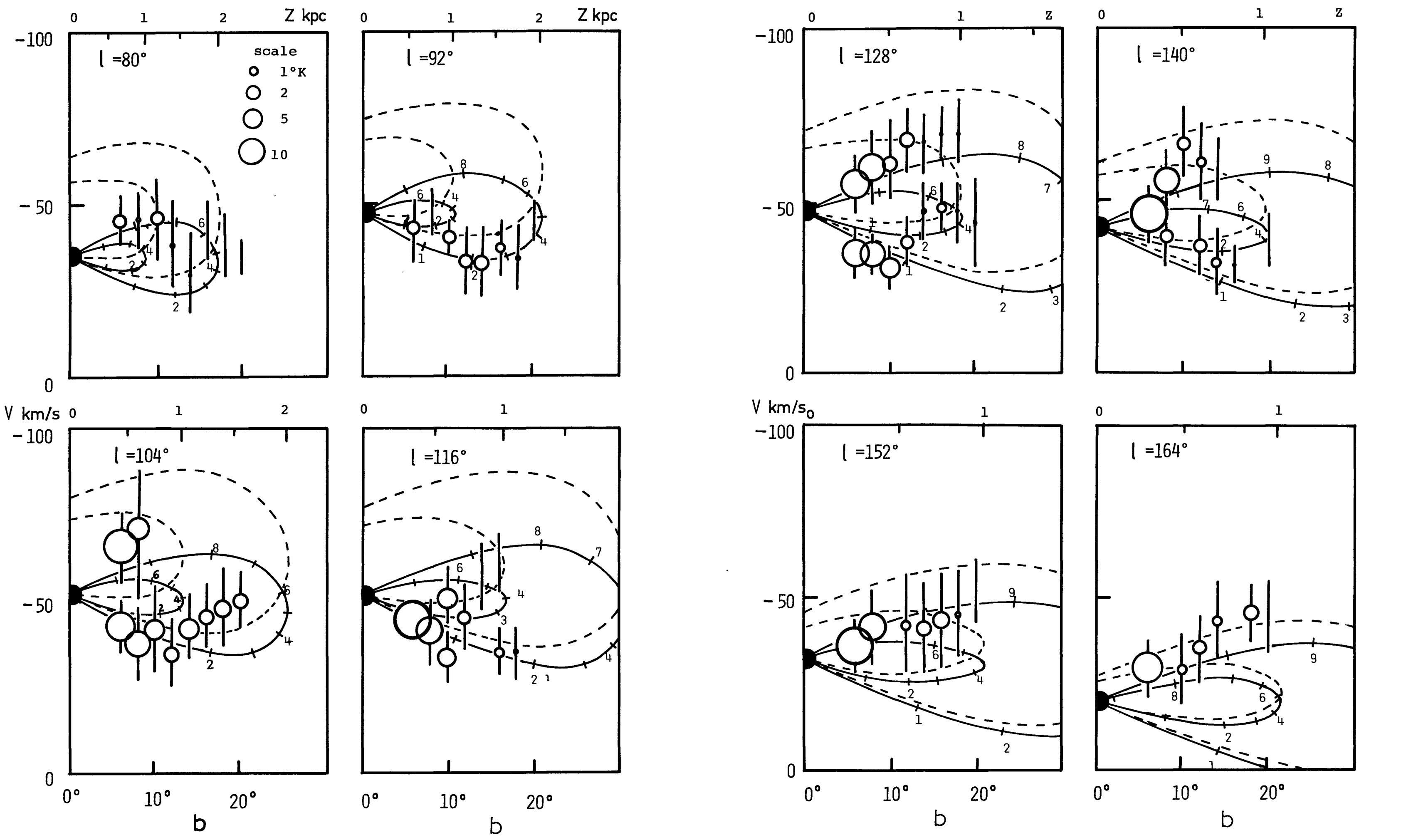

Fig. 1a.

Fig. 1. (a) Calculated loci on the $(b-v)$ diagram for gas clouds ejected in the z-direction out of the "active region" fixed to the gaseous disk (full lines). Dashed lines show the loci for the case in which the active region is fixed to the spiral pattern (see text). The age of the cloud is indicated in units of 10^7 years. Also presented are the observed 21-cm line data due to Kepner (1970); the area of a circle is proportional to the intensity and the length of the bar gives the velocity width of a gaussian component. Note the close agreement between the model loci for $Z=2$ kpc and the data. (b) Velocity-latitude diagrams at lower latitudes. Thick lines: ridges taken from the $(b-v)$ countour maps of H I line emission observed by Henderson (1966) for the Perseus arm. Thin lines: calculated loci for a gas cloud ejected out of the galactic plane with a maximum height of $Z=2$ kpc. The arrows indicate the direction of the motion of the cloud

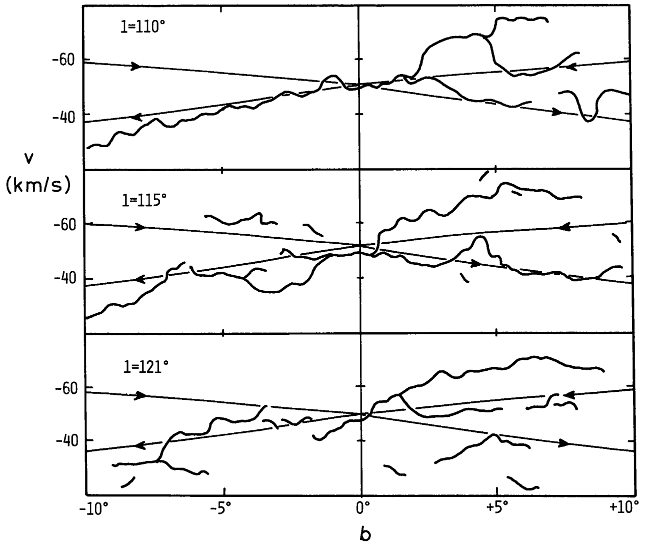

Fig. 1b.

We assume that the horizontal component of motion of gas above the galactic plane follows the same rotation law as in the galactic plane. The line of sight velocity to be observed at the sun is

$$v = v_z \sin b + V_0 \cos b\,, \tag{4}$$

where V_0 is the radial velocity of the gas due to the galactic rotation in the galactic plane just below the cloud. When the location of a cloud with which we are concerned is given, V_0 for the cloud is evaluated from Schmidt's (1965) rotation curve. The radial velocity V_0 for the Perseus arm in the galactic plane is taken from Westerhout (1969) (see Fujimoto and Tanahashi, 1971) and Weaver (1970); in the present model calculation we use a smoothed $(l-v)$ curve as shown in Fig. 2 ($b=0°$).

Thus given a longitude l and a latitude b, we can calculate the line of sight velocity of the cloud for a given value of the ejection velocity, or the maximum height of the cloud using Eqs. (1) and (4). We can obtain a $(b-v)$ diagram for a fixed longitude, and also a $(l-v)$ diagram along a constant latitude.

We show the calculated $(b-v)$ diagrams for the Perseus arm in Fig. 1a and b for cases of maximum heights $Z=1$ and 2 kpc. The age t of the ejected gas is indicated by the numerals on the model loci in units of 10^7 years. We superimpose on Fig. 1a observed data by Kepner (1970) who gave $(b-v)$ plots of gaussian components of H I gas at $b=+6°-+20°$ ($\Delta b=2°$), $l=48°-200°$ ($\Delta l=4°$). Most of the observed points for the Perseus arm are well fitted by the model loci for $Z=2$ kpc: good fits between the calculated diagrams and the observed ones are obtained for 21 cases out of 23 of her observations at $l=80°-168°$. The two cases for which no satisfactory fitting was obtained are located at $l=100°$ and $l=112°$. However, these two cases could be explained as a result of the superposition of some loci of different ejection velocities.

Figure 1b shows an example of comparison of the calculated $(b-v)$ diagrams for $Z=2$ kpc with observational data at lower latitudes ($b=-10°-+10°$, at $l=110°$, 115° and 121°) for the Perseus arm. Thick lines in the figure show ridges of the brightness temperature of H I line emission taken from $(b-v)$ contour maps observed by Henderson (1966), who gave the maps at $b=-10°-+10°$, $l=16°-230°$ with $\Delta l=5°$. The calculated loci roughly fit the observed ridge lines. However the fitting is not so good as in Fig. 1a because of the complicated nature of the motion and distribution of H I gas in and near the galactic plane.

The splitting of the Perseus feature into two separate ones on the $(b-v)$ plane at intermediate latitudes (Kepner, 1970) is thus naturally interpreted in terms of the ascending and descending motions of gases above the Perseus arm. We find also that the splitted branches tend to coincide with each other and with the main Perseus feature near and at the galactic plane.

In Fig. 2, we show the calculated $(l-v)$ diagrams for $Z=2$ kpc at some fixed latitudes: $b=0°, 6°, 12°$ and 18°. A branch corresponding to the rising gas is indicated as R-feature, and the falling gas as F-feature. Superposed data in the figure at $b=0°$ are due to Westerhout (1966: see Fujimoto and Tanahashi, 1971), and those at $b=6°$, 12° and 18° are due to Kepner (1970) and Verschuur (1973b). The apparent splitting of the Perseus arm into two features in the $(l-v)$ plane, i.e., the P- and α-features (Verschuur, 1973b) or the P_i- and P_0-features (Kepner, 1970) at intermediate latitudes, can thus easily be explained by the coexistence of the rising and falling motions of gas in the space just above the main Perseus arm.

In Fig. 3, we display a map of the H I arm projected onto the galactic plane for the Perseus region as seen from the galactic north pole. The location of gas has been determined from the H I velocity data, using the Schmidt rotation model. In deriving the locations of the P(rising)- and α(falling)-arms at $b=6°$, we have corrected for the effect of the z-motion of our model for $Z=2$ kpc. Then we find that the P- and α-arms coincide spatially not only with each other but also with the Perseus arm at $b=0°$ which has been derived from the $(l-v)$ curve shown in Fig. 2 ($b=0°$). For a comparison, we show the positions of the arms at $b=6°$ not corrected for the z-motion, which are separated largely from each other.

From the above arguments we can conclude that all of the gas above the spiral arm is ejected out of the arm with roughly the same velocity of about 70 km/s in the z-direction. The gas rises and falls somewhat freely through the galactic halo. Fairly good fits of the observed diagrams to calculated ones indicate that the ambient gas hardly affects the motion of the ejected gas

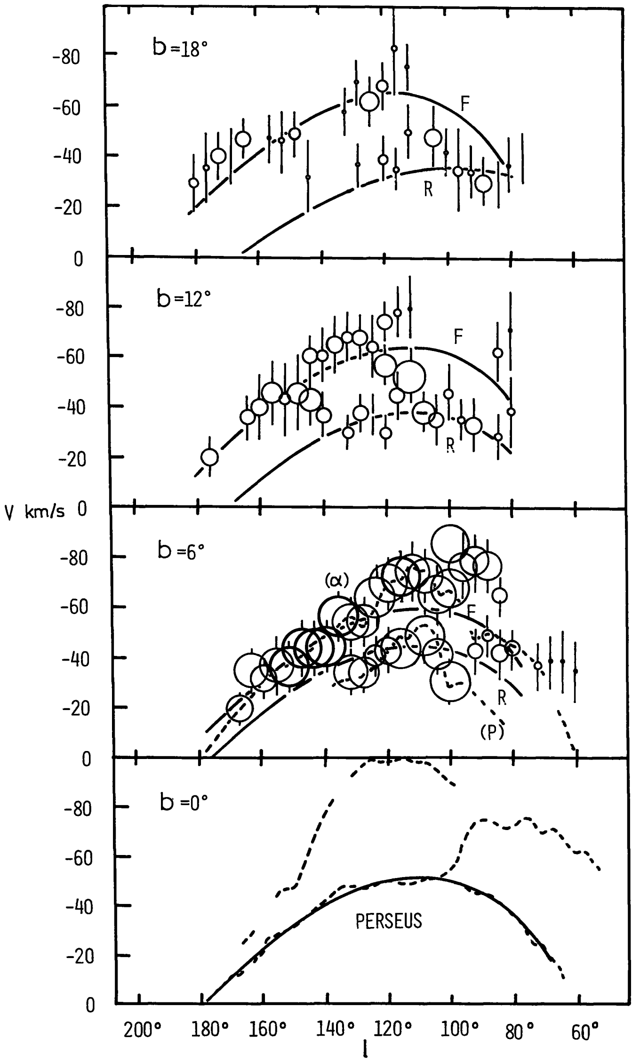

Fig. 2. Calculated $(l-v)$ diagrams for $Z=2$ kpc at $b=18°$, 12°, 6°, and a smoothed Perseus feature at $b=0°$ which is used in the calculation. Data are due to Kepner (1970; circles and bars at $b=18°$, 12° and 6°), Verschuur (1973b; dashed lines at $b=6°$), and Fujimoto and Tanahashi [1971; dashed lines at $b=0°$, who used data by Westerhout (1969)]

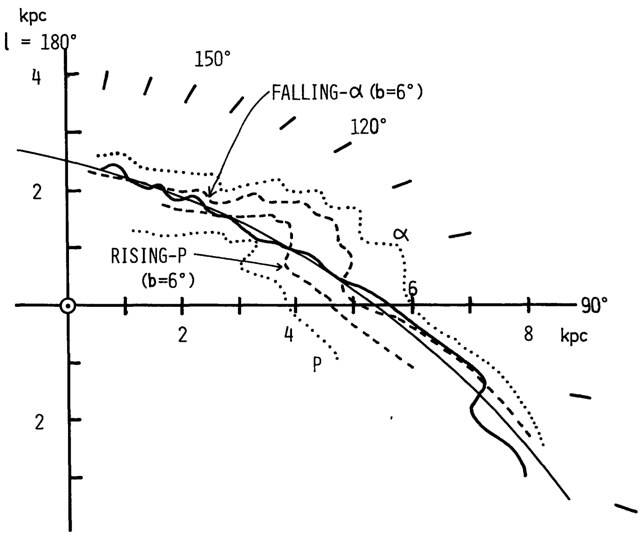

Fig. 3. H I Perseus arms projected on the galactic plane. Thick line: the Perseus arm at $b=0°$ derived from observed 21-cm line data. Thin line: model Perseus arm at $b=0°$ on which the calculation is based. Dotted lines: P- and α-arms at $b=0°$ not corrected for the z-motion. Dashed lines: P(rising)- and α(falling)-arms observed at $b=6°$ corrected for the z-motion with $Z=2$ kpc. Note that the rising and falling arms coincide not only with each other but also with the main Perseus arm at $b=0°$

clouds: the drag force due to the ambient gas in the galactic halo below $z=2$ kpc is negligible. From this fact we estimate the upper value of the density of the ambient gas in the space up to 2 kpc as 2×10^{-3} hydrogen atoms cm^{-3} (see Paper I).

We have shown that roughly a constant ejection speed (~70 km/s) is obtained over wide range of the Perseus arm. However it is natural to consider that the ejection speed has a large dispersion around its mean value. Then the dispersion will give rise to a dilution of the gas in spite of the increase of residence time with height. The dilution will result in a decrease of columnar density of the observed H I gas with latitudes, which is really recognized in the data as shown in Figs. 1 and 2.

We have also calculated some $(b-v)$ diagrams for a second case, namely that the "active region" ejécting gas is fixed to the spiral pattern: the gases land on the leading side of the spiral arm after performing their ascending and descending flights. If this case is confirmed observationally, we can suppose that the ejection of gas is directly driven by the pass of the gas through the spiral pattern. In the calculation we have taken $i=7°$ for the pitch angle of the arm and $\Omega_p=13.5$ km/s/kpc for the pattern speed relative to the disk (Lin *et al.*, 1969). In Fig. 1a, we show the calculated loci in this case by dashed lines. We find, however, no improvement for the model loci and we need not take into account the possibility for such a direct mechanism at the present time.

III. Spatial Distributions of the Rising and Falling Gases and Early-type Stars in the Perseus Region

The spatial distribution of early type stars and their kinematical correlation with the H I Perseus arm have been extensively investigated by many authors (Becker, 1961; Abt and Bautz, 1963; Rickard, 1968; Courtés *et al.*, 1969; Roberts, 1973; Verschuur, 1973b; Minn and Greenberg, 1973). Verschuur (1973b) has shown that the P-arm of H I gas is associated with early type objects such as O-associations, OB-clusters and H II

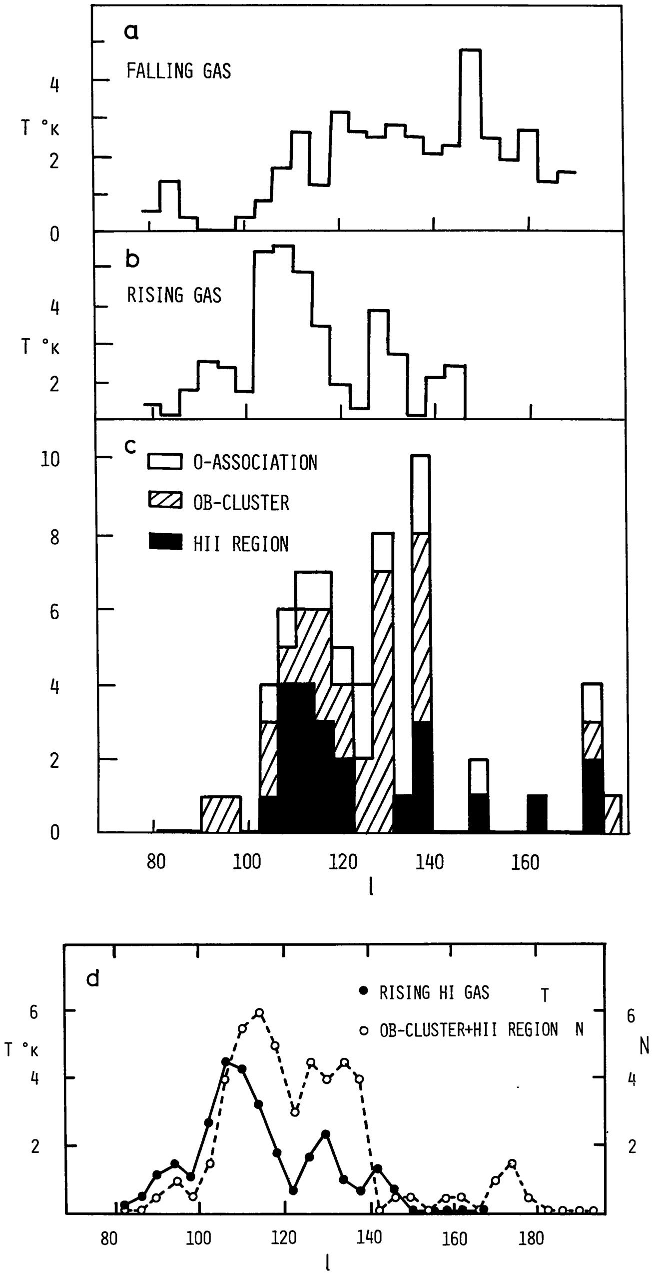

Fig. 4. (a) Mean brightness temperature of 21-cm line emission averaged over $b=8$–$12°$ for the falling gases above the Perseus arm. (b) Same as 5a but for the rising gases. (c) Numbers of H II regions, open clusters, and O-associations in the Perseus region. (d) Comparison of the distribution of 21-cm line brightness of rising gases with that of the early type objects. Each point has been taken from 5d and 4c by a running average of the neighbouring two points. A good spatial coincidence is seen between them

regions, while the α-arm is not associated with such a stellar arm.

In this section we compare spatial distributions of the rising and falling gases with that of the early type stars. We plot mean brightness temperature of the observed H I emission averaged over latitudes between $b=8°$ and $20°$ for the rising and falling gases separately in Fig. 4a and b as a function of galactic longitude. Figure 4c shows a histgram for the number of O-associations, OB-clusters and H II regions, which belong to the Perseus arm. The data are from Becker and Fenkart (1970), Rubin *et al.* (1962), Courtés *et al.* (1969), Humphreys (1970) and Roberts (1972). Figure 4d shows running averages between neighbouring two points in Fig. 4b and c. We find a good spatial correlation of gases in the rising phase with the young objects, especially with OB-clusters and H II regions, while no significant correlation is found between these objects and the falling gases. These facts indicate that the ejection of the gases is intimately associated with the young luminous stars.

As shown in Section II, the motion of the ejected gases is represented by loop-shaped trajectories on the $(b-v)$ plane. Figure 1a shows, however, that the loop is not complete, but some parts of the loop or arcs are missing. This fact suggests that the ejection is not continuous but rather intermittent, although the ejection speed is roughly constant. From Fig. 1a, in which the age of the cloud is indicated on the locus, we can find that the ejection of gas lasts for about 3×10^7 years. This value, which is a few times the mean life-time of OB-stars, can be regarded as a duration of an "activity" of the ejection region. If this "active region" is identical with a galactic cluster or an association, the member stars are considered to be born spanning a time scale of 3×10^7 years.

In Fig. 4, we find an obvious lack of the P(rising)-arm of H I gas beyond $l=140°$ at intermediate latitudes, and also find that the stellar arm does not extend in the longitudes of $l>140°$. This cutoff of the stellar arm is real because no significant absorbing matter is observed between the sun and the Perseus arm in these directions (FitzGerald, 1968; Lynds, 1968). On the other hand, the α(falling)-feature is traced continuously up to $l=170°$ or more in the $(l-v)$ diagram or on the distribution map as projected onto the galactic plane (Figs. 2 and 3). This fact suggests that the main Perseus arm beyond $l=140°$ is not active enough to give rise to the ejection of gases at present, but more than 3×10^7 years ago it must have ejected gases intensely with a z-velocity of 70 km/s or so. The gases which were ejected at that time are now observed as the falling gases responsible for the α-arm at intermediate latitudes. In other words, the α-arm is a remnant of the stellar Perseus arm which was active enough some 10^7 years ago.

IV. Enhancement of Background Continuum Radio Emission above the Perseus Complex Region

A map of 820 MHz radio continuum emission is reproduced in Fig. 5 in galactic coordinates from

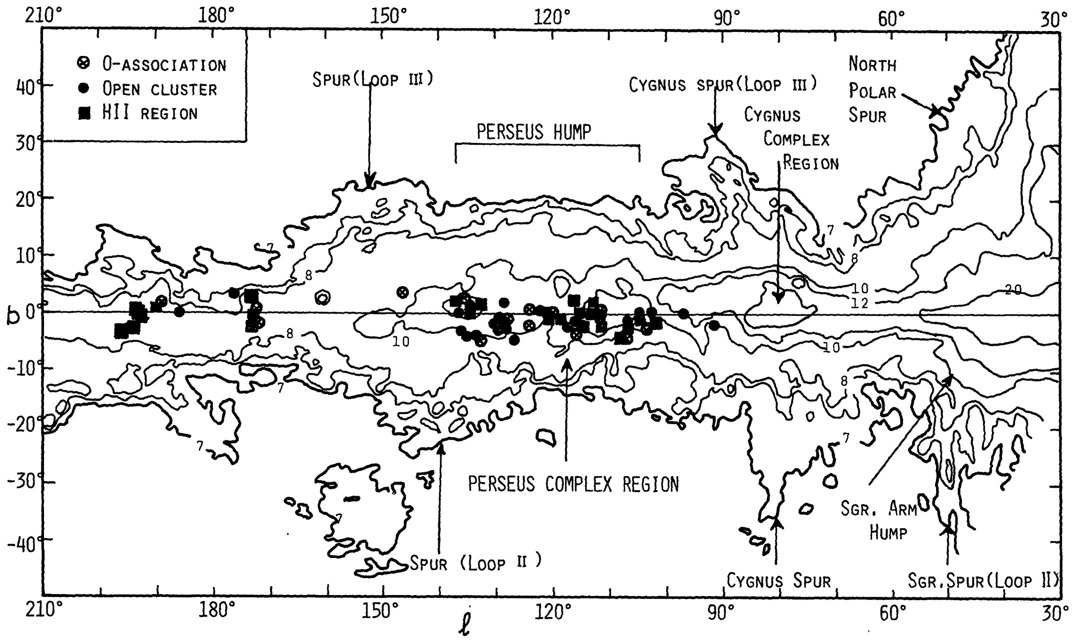

Fig. 5. Distribution on the (l, b) plane of H II regions (■), open clusters (●), and O-associations (⊗) belonging to the Perseus arm as superimposed on the map of radio continuum emission at 820 MHz (Berkhuijsen, 1971). A wide hump of radio contour lines ("Perseus hump") at $l = 100°–140°$ is associated with the region where the young objects are concentrated ("Perseus complex"). Some other pronounced features such as galactic spurs, the Cygnus complex region, and the Sagittarius hump (or step) are indicated with the arrows. Numerals on the contour lines indicate the brightness temperature in units of °K

Berkhuijsen (1971), on which we have superimposed positions of OB-clusters, O-associations and H II regions belonging to the Perseus arm. We find that contour lines of radio continuum have a tendency to hump toward the northern and southern hemispheres at various longitudes. Some of them are so called galactic spurs, positions of which are indicated by arrows. Of these, it is notable that the Cygnus complex region at $l = 80°$ is associated with two prominent spurs which emerge vertically from the galactic plane into the northern and southern hemispheres.

In addition to these spurs, we can recognize a wide hump of contour lines toward the northern hemisphere at $l = 100–140°$, $b = 10–20°$. Such a hump in the same direction is also recognized obviously on the maps of background emission at 408 MHz (Seeger *et al.*, 1965), and at 178 MHz (Turtle and Baldwin, 1962). This hump (which we call hereafter the "Perseus hump") is in good coincidence with the concentration of young objects ("Perseus complex region") as plotted on Fig. 5, and also with the rising gases above the Perseus arm.

The Perseus hump exists only at positive latitudes: the radio emission is somewhat smaller at negative latitudes than at neighboring longitudes. As will be discussed in the next section, this asymmetric behavior could be explained if the origin of the hump is due to Parker (1969) type instability of magnetic field with cosmic ray gas.

V. Interpretation and Discussion

Finally we consider an interpretation of the phenomena described in the preceding sections and discuss some related problems.

The rising H I gases exist above the regions where early type stars such as OB-clusters and H II regions are concentrated ("Perseus complex region"), and are associated with enhanced radio continuum emission ("Perseus hump"). These facts suggest the following mechanism to accelerate the gases in the z-direction.

Above the region where young objects such as OB stars are born in large quantity, strong UV light from these objects exerts excess radiation pressure in the z-direction on interstellar dust grains. Since the radiation pressure promotes the Parker (1969) type instability above the galactic plane (Chiao and Wickramasinghe, 1972), the occurrence of the instability is highly enhanced above the luminous region of the spiral arm. The Parker type instability developes into nonlinear inflation of magnetic field due to locally enhanced pressure of cosmic rays which are supplied from frequent supernova explosions in these regions. The inflating magnetic field will accelerate a significant amount of upper-lying gases up to a final speed of 50–100 km/s in the z-direction before they drop down along the magnetic lines of force (Fujimoto *et al.*, 1974). These gases are the rising H I gases.

The accelerated gases rise up to a height of about 2 kpc and fall freely toward the galactic plane owing to the gravitational force. The rising gases correspond to the P-feature in the observed $(l-v)$ diagrams at intermediate latitudes, and the falling gases to the α-feature.

According to the present interpretation, synchrotron radio emission due to the inflating magnetic field and cosmic ray electrons should be associated with the gases in the rising phase. This radio emission naturally accounts for the observed wide hump of the background continuum emission above the luminous region of the Perseus arm at $l=100°-140°$ ("Perseus hump": Fig. 5).

Sofue (1973) and Sofue *et al.* (1974) have interpreted the galactic spurs in terms of the galactic shock waves (Fujimoto, 1966; Roberts, 1969; Roberts and Yuan, 1970; Tosa, 1973); some of the spurs, those emerging from the galactic plane at $l=80°$ into the northern and southern hemispheres, for example, are due to a tangential view of the nonthermal radio emitting regions (nonthermal banks) which are located above and below the spiral arm. The emitting regions are produced by inflations of magnetic field with cosmic rays triggered by the Parker type instability along the galactic shock wave regions, where the star formation and subsequent supernova explosions are frequent. This picture for the spurs is in good agreement with the present picture of the high z-extension of gas associated with the radio continuum enhancement above the Perseus arm.

The Parker type instability will not necessarily develop symmetrically above and below the galactic plane, so the nonthermal emission associated with the inflating magnetic field in high z region would be asymmetric above and below the galactic plane. In fact, as mentioned in Section IV, the Perseus-hump shows asymmetric behavior at positive and negative latitude. Most of the galactic spurs also show strong north-south asymmetry (Sofue, 1973).

Next we consider the effect of the radiation pressure on the behavior of dust grains high above the spiral arm. The dust grains are not only carried away with the ejected gas, but are also expelled from the gaseous disk toward the galactic halo by the strong radiation pressure due to the newly born OB stars (Chiao and Wickramasinghe, 1972). The radiation pressure exerts force only on the dust grains. Thus the dust grains tend to accumulate in the high z region, being supported against the gravitational force by the radiation pressure from the active regions of the spiral arm. The H I gases, however, fall toward the galactic plane because no mechanism acts to support them.

Chiao and Wickramasinghe (1972) have given equations for the drift velocity of dust grains through the neutral hydrogen gas. If we assume that the temperature of the H I gas in the high z region is 10^2–10^3 K and the density is about $10^{-2}\,\mathrm{cm}^{-3}$, the drift velocity is estimated as 10 to 20 km/s for the radiation pressure equal to that at $z=50$ pc in the normal interstellar space. Since the radiation pressure above the Perseus complex region is considered to be much greater than that in the normal interstellar space because of the concentrated OB stars, the drift velocity in the region concerned will be somewhat larger than this value. Hence an appreciable amount of the dust grains may be separated from the rising gases and may accumulate in the high z-region.

In fact, it is characteristic of the distribution of galaxy counts (Steinlin, 1962; Shane and Wirtanen, 1967) that the zone of avoidance of galaxies widely extends into the northern hemisphere at $l=100°-140°$, $b=20°-30°$. An enhancement of absorbing matter is found in these directions which has spatial correlation with the Perseus complex region. However, we cannot exclude the possibility that this enhanced absorption is entirely due to irregularities of the local interstellar absorbing matter near the sun.

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