MOLECULAR SPECTROSCOPY AS DIAGNOSTICS OF OUTER ATMOSPHERE OF COOL LUMINOUS STARS: QUASI-STATIC TURBULENT MOLECULAR FORMATION ZONE AND STELLAR MASS-LOSS

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Abstract

The origin of mass-loss in cool luminous stars is still obscure; several known mechanisms such as thermally driven wind, radiation-driven wind(via dust),wave-driven wind etc all have serious difficulties, if examined in the light of recent observations. At the same time,recent observations in the infrared and radio spectral domains revealed that outer envelope of red (super)giant stars has highly complicated spatial and velocity structures, while inner envelope may have new component that had not been recognized before. For example, recent high resolution infrared spectroscopy revealed a possible presence of a quasi-static turbulent molecular dissociation zone somewhere in the outer atmosphere. This new component may represent a transition zone between the warm chromosphere and the huge expanding molecular envelope, and may be a cool component of chromospheric inhomogeneity or a moleclar condensation in a cool corona extended by turbulent pressure. Such a result can be regarded as observational evidence in support of a recent theory of autocatalytic molecular formation by thermal instability due to molecular cooling. Thus, observation and theory consistently show the presence of a new component - quasi-static turbulent molecular formation zone - in outer atmosphere of cool luminous stars, and a possibility of a unified understanding of outer atmospheric structure and mass-loss, in which turbulence may play important role, can be proposed.

I. Introduction

The importance of mass-loss in the late stages of stellar evolution, represented by the red giant phase, has long been known, but the origin of the massive cool wind from red giant stars is still not clear. This difficulty of understanding the origin of massive cool wind from red (super)giant stars should undoubtedly be related to our poor understanding of the physical structure of the outer atmosphere. This is evident if we remember the case of the Sun, in which the solar wind has been understood as a necessary consequence of the outer atmospheric structure consisting of the photosphere,chromosphere,transition layer,and corona. Thus, more physical understanding of the outer atmospheric structure of red giant stars, which may radically be different from that of the Sun, should be a prerequisite in understanding the mechanism of mass-loss in red giant stars.

In consideraing the problem noted above, one important characteristic of the cool wind from red giant stars is that the observed flow velocity is much smaller than the escape velocity at the stellar surface, in marked contrast to that from hot luminous stars in which observed flow velocity exceeds the escape velocity at the stellar surface. This fact implies that the cool wind in red giant stars cannot originate from the stellar surface but should originate from the outer layer at least several stellar radii above the stellar surface, while stellar wind from hot luminous stars is originating from the stellar surface. Thus, to clarify the origin of cool wind in red giant stars, it should be most important to know the physical structure of the layer located at several stellar radii above the stellar surface. For this purpose, molecular spectroscopy,both in the infrared and radio spectral domains,should be most effective because of the relatively low temperature of such a region,while relatively hot region in outer atmosphere has been probed by atomic spectroscopy such as by IUE.

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In this contribution, we first examine the known mass-loss mechanisms in the light of the recent observations(Sect.II),and then we review some recent infrared and radio observations that may be relevant to our understanding of the outer atmospheric structure and mass-loss phenomena(Sect.III). Based on these observations, new picture of the outer atmosphere of red (super)giant stars is proposed and its implications on circumstellar chemistry as well as on mass-loss phenomena are discussed(Sect.IV).

II. Difficulties of Mass-Loss Mechanisms in Red Giant Stars

As to the origin of mass-loss in cool luminous stars, several possibilities have been proposed, but none of them could provide satisfactory answer yet. As noted in Sect.I, the cool wind should originate not in the stellar surface but in outer layer at least several stellar radii above the stellar surface. We already know such a case in the thermally-driven wind from the hot corona of the Sun. However, the difficulty to apply the theory of thermally-driven wind to cool luminous stars has already been recognized at an early time(e.g., Weymann, 1963). More recent discovery of non-existence of hot transition region(and hence of corona) in these stars by IUE observations(Linsky,Haisch,1979) finally disclosed that the origin of mass-loss in cool luminous stars may be radically different from that in solar type stars.

Now,if hot corona plays little role in accelerating wind in cool luminous stars, how about a role of chromospheres? In fact,it was suggested that the flow velocity in chromospheres is nearly half of the terminal flow velocity(Reimers,1975), or that it already reaches the terminal flow velocity in the upper chromosphere and hence mass-loss out-flow already starts in chromospheres(Goldberg,1979). However, it must be remembered that the observed extension of the chromosphere, although much extended than in the Sun, is within a few stellar radii, as shown by H α images(e.g., White, Kreidl, Goldberg,1982; Hebden,Eckart,Hege,1986) or by radio continuum emissions(e.g., Wischnewski, Wendker,1981; Drake, Linsky, 1986). Then, observed flow velocity in the chromosphere is still much smaller than the local escape velocity in such an extended chromosphere. Thus, outflow in stellar chromospheres cannot be a direct origin of stellar mass-loss,unless there is further acceleration mechanism in the chromosphere. Despite extensive efforts,however,no such mechanism has been found(e.g.,Caster,1981). Thus, the material moving outward in chromospheres should eventually be decelerated. In fact, evidence of infall material is observed by FeII emission lines in α Ori (Boesgaard,Magnan,1975), although FeII emissions do not necessarily appear red shifted in red giant stars(Boesgaard, 1981). Also recent high resolution observations of several M-giant stars by IUE revealed that the velocity field in the chromosphere of red giant stars is highly compicated. For example, UV absorption lines gave large positive velocity while some UV emission lines showed negative velocity relative to the photospheric lines(Eaton,Johnson,1987). In this connection, it is interesting to note that a model which pictures the chromosphere as a complicated "fountain" of streaming material consisting of upflows and downflows has been suggested from observed line profiles of α Ori, after recognizing that Alfven wave driven model could not reproduce observed line profiles(Hartmann, Avrett, 1984).

Under such a situation, a mechanism of mass-loss that can be plausible in cool luminous stars may be radiation-driven model. Especially, it is known that radiation pressure on dust can effectively accelerate mass-loss outflow, once dust could be formed. The major problem in this case is where the dust could be formed. It is generally difficult to make dust near the photosphere because temperature may be too high for dust to be formed. Recently, a possibility to produce dust in the chromosphere by the so-called condensation instability is proposed(Stencel,Carpenter,Hagen, 1986). Although this is an interesting idea that deresrves further attention(Sect. IV), it is not clear if dust could be formed near the star. In fact, recent speckle interferometry of many evolved cool stars in the near infrared has shown that there should be dust-free zone extending out to several stellar radii around the central star(Dyck et al.,1984; Ridgway et al,1986). Also, in the case of red supergiant star α Ori, direct infrared imaging revealed that the dust-free zone may be as large as 20 stellar radii(Bloemhof,Townes,Vanderwyck,1984). Thus, dust may be formed pretty far from the stellar surface, but such a dust formation is only possible if the gas density of the dust condensation point is high enough, as has already been noted by Kwok(1975). One possibility to have high density region in outer atmosphere is to levitate the mater above the photosphere by stellar pulsation(e.g.,Jura,1986;Fedeyev, 1988),but this applies only to pulsating stars at best. For this reason,more consistent understanding of the outer atmospheric structure should be needed before we can accept(or not accept) the dust-driven model of mass-loss in red (super)giant stars.

On the other hand, the velocity structure of the outer atmosphere has been measured by radio interferometry: For example, Chapman and Cohen(1986) showed that the velocity extents of the maser emissions such as of SiO, H_2O, and OH increase systematically with angular extents, and they interpreted this fact as showing the continuous increase of expansion velocity with radial distance. They pointed out that the driving force per unit mass must be increasing with the distance from the star to explain such a velocity structure. However, it is difficult to provide the required driving force by radiation pressure on dust in the inner envelope because of the absence of dust itself as noted above. Furthermore, masers of SiO and H_2O do not necessarily show clear expansion pattern(see Sect.III), and it is not sure if the inner envelope is really expanding. For carbon stars, however, carbon grains can condense at relatively high temperature near the photosphere,and a self-consistent model of dust-driven mass-loss can be constructed(e.g.,Sedlmayr,1988). Even though, the solution of the equations of stellar wind may depend on the boundary condition, which further depends on the inner structure of the circumstellar envelope,for which little is known yet, as will be discussed in the next section.

Also, one classical question is whether dust formation initiates mass-loss or whether dust is formed as a result of mass-loss. It is to be noted that the latter process may be rather easy, once mass-loss occurs by another mechanism. This problem can be examined on the basis of recent observations of CO radio emission lines, by which stellar mass-loss rate has been determined with better accuracy than by any other method for a large sample of red giant stars, and terminal flow velocities have also been determined with high accuracy(e.g.,Knapp,Morris,1985). The result revealed that the momentum in the stellar wind and that in the stellar radiation do not necessarily show good correlation(e.g.,Zuckerman,Dyck,1986). Also, a necessary condition for the winds to be accelerated by radiation pressure on dust($\dot{M}v < L/c$) seems to be not fulfilled for considerable number of stars(Zuckerman,Dyck,1986; Knapp,1986). Thus, the question addressed at the beginning of this paragraph still remains open.

Finally, it is also evident that radiation pressure on dust cannot explain all the mass-loss phenomena in red giant stars, since dust is not found in K and early M giant stars, which also show considerable mass-loss in general. In fact, recent IRAS survey revealed infrared excesses that show the presence of dust only in stars later than M3-4III(Hacking et al,1985). Thus, although dust-driven mass-loss could be successful in a limited case such as cool carbon stars with massive wind(e.g., Sedlmayr,1988),it could not provide unified understanding of mass-loss phenomena in red (super)giant stars in general. Clearly, more unified understanding of mass-loss in cool luminous stars should be looked for.

III. Molecular Spectroscopy of the Outer Atmospheres of Red Giant Stars

A brief survey outlined in the previous section reveals that more information on the intermediate zone where mass-loss outflow starts should be needed. As noted in Sect.I,such a region of outer atmosphere can best be probed by molecular spectroscopy especially in the infrared and radio spectral regions.

First,one important result of the infrared molecular spectroscopy is a discovery of stationary CO layer in Mira type variable star χ Cyg, in which CO lines that stay stationary have been clearly separated from the photospheric CO lines that show cyclic Doppler-shifts by the large amplitude pulsation of the photosphere in time series spectra(Hinkle, Hall, Ridgway, 1982). It was suggested that the stationary CO layer may be located at several stellar radii above the stellar surface, since excitation temperature of the stationary CO layer of χ Cyg was found to be 800K.

A possible presence of a similar stationary layer in red supergiants has previously been suggested by Hall(1980). The recognition of such a stationary layer by spectroscopic observations is generally difficult, because spectral lines originating from such a layer show little Doppler shift against photosheric lines in non-Mira stars. More recently, however, a possible presence of a static layer has been demonstrated from a detailed analysis of CO overtone bands in several M-giant stars of the spectral types later than M4III as well as in red supergiant stars such as α Ori (Tsuji, 1986b, 1987a,b). Although CO lines originating from such a static layer in nornal red (super)giants cannot be separated by Doppler shifts against photospheric lines, they can be recognized by the following evidences:

(1) Quantitative spectroscopy applied to the CO first overtone bands in high resolution infrared spectra showed reasonable success for M-giant stars as cool as M7III, and equivalent widths of weak and medium strong CO lines, which are also relatively high excitation lines, can quantitatively be well understood by model stellar atmosphere with well defined parameters(Tsuji,1986a). However, strong CO lines, which are also low excitation lines, show systematic excess as compared with expected ones based on the same model atmosphere(Fig.3 of Tsuji,1986b).

(2) The low excitation lines show shifts and asymmetries that indicate excess absorption in blue wing in some stars and in red wing in other stars(Figs.4 and 5 in Tsuji, 1986b).

(3) Radial velocities show differential time variations between low and high excitation lines. For example, low excitation lines remain almost stationary while radial velocities of high excitation lines show appreciable changes, possibly due to small amplitude pulsation of the photosphere, in the case of α Her(Fig.1 in Tsuji, 1987a).

While the intensity anomaly alone(item 1 above) can be due to our poor understanding of atmospheric structure and/or of line formation in the upper atmosphere, peculiar line shift and line asymmetry(item 2) as well as differential time variation note above(item 3) suggest that at least a part of low excitation lines should be originating not in the photosphere but in an extra layer well separated from the photosphere. We tentatively refer this separate extra layer as CO absorption layer (the "layer" does not necessarily imply that it is well stratified but rather it can also be an inhomogeneous component in outer atmosphere, and the "layer" is used in this extended meaning in what follows).

Now, the problem is how could we separate the contribution by the CO absorption layer from the stronger photospheric component. For this purpose, we compared the observed profiles with predicted ones based on model atmospheres and found appreciable residual absorption for low excitation lines while no residual for high excitation lines. Then, the contribution by the CO absorption layer has been separated by subtracting the photospheric contribution from the observed profile,in low excitation CO lines. A detailed analysis on separated excess CO absorption gives the results as follow(as for detail, see Tsuji,1987b):

(1) Excess CO absorption can be seen not only in 2-0 band but also in 3-1 band, and excitation temperatures of the CO absorption layer are between 1000 and 2000K.

(2) Turbulent velocities in the CO absorption layer are larger than 5 km/s in red giants and larger than 10km/s in red supergiants.

(3) The CO column density of the absorption layer is as high as $10^{20}/\mathrm{cm}^2$.

(4) The movement of the CO absorption layer relative to to the photosphere is very small, either positive or negative, but it show expansion of a few km/s against the central star for the cases of known stellar velocity(by thermal radio lines).

The physical parameters of the CO absorption layer in red (super)giant stars are very similar to those of the stationary layer of Mira variable star χ Cyg mentioned above(Hinkle,Hall,Ridgway,1982). Thus,the presence of a separated stationary CO layer may be not restricted to Mira variable stars, but rather it may be a basic characteristics of red giant and supergiant stars in general.

In this connection, it is to be remembered that H_2O and SiO maser emissions also showed the presence of a non-expanding turbulent layer within some 10 stellar radii of late-type giant stars(e.g.,Reid,Moran,1981). Maser emissions are powerful probes of the inner circumstellar envelope, especially if high resolution spatial interferometry could be applied. For example, VLBI observations of SiO masers showed that the masers occur within a few stellar radii in outer atmosphere, but do not show any systematic expanding patern(Lane,1984). Thus,SiO masers may originate in cloudlets of rather high density in the turbulent region of the inner circumstellar envelope (Alcock,Rose, 1986). Also, high resolution observation of H_2O maser emissions for several late-type stars by VLA revealed that H_2O features appear to be unresolved knots distributed over not more than 20 stellar radii(Johnston,Spencer,Bowers,1985). Thus, both thermal absorptions(CO infrared lines) and non-thermal emissions(H_2O and SiO masers) consistently show the presence of molecular formation zone, roughly between a few stellar radii and some 20 stellar radii.

In contrast to a static molecular formation zone in the inner part of the circumstellar envelope, expanding molecular envelopes are relatively easy to recognize. However, it is only recently that some details of velocity and spatial structures of the expanding envelope have been made clear. For example, it is interesting to remember that presence of multiple velocity components in expanding CO envelopes has been found from the analysis of the fundamental bands of CO in α Ori(Bernat et al.,1980) as well as in normal red giants(Bernat,1981): The expanding CO envelopes are charcterized by much lower excitation temperatures, by smaller turbulent velocities,and by smaller column densities, as compared with those of the static CO absorption layer discussed above. It is natural to suppose that these expanding CO components might have been outflowed from the static CO layer.

Further, expanding molecular envelope can be traced by the pure rotational transitions in the millimeter wavelength region out to some 10^5 stellar radii(e.g., Zuckerman,1980; Olofsson,1985). One interesting feature of such a huge molecular envelope is that it may not necessarily be spherically symmetric(e.g.,Chapman,Cohen, 1986). Furthermore,asymmetric profiles suggesting bipolar structure has been observed in M-type giant such as OH231.8+4.2(Morris et al.,1987) as well as in carbon star such as V Hya(Tsuji et al.,1987). Such a bipolar structure of the outer envelope may be related to binarity(Morris,1981). Recently, infrared speckle interferometry also showed that the mass-loss geometry may be bipolar in nature,for several evolved giant stars(e.g.,Dyck et al.,1987; Cobb,Fix,1987). It is still not clear if bipolar structure of the outer envelope is a general feature of mass-losing stars, and more detailed observations on spatial structure of outer envelopes of mass-losing stars should certainly be important.

IV. A New Component of Outer Atmosphere of Red Giant and Supergiant Stars: Quasi-Static Turbulent Molecular Dissociation Zone

A survey of recent observations in the previous section revealed that there should be a new component in the outer atmosphere of red (super)giant stars;molecular formation zone,tentatively referred to as the CO absorption layer. This CO absorption layer identified in Sect.III shows almost no expansion, in contrast to the expanding molecular envelope so far known, but has large turbulent motion. Thus, we may assume a presence of a quasi-static turbulent molecular dissociation zone somewhere in the outer atmosphere. One possibility is that this zone may represent a transition zone between the warm chromosphere and the massive cool wind in red (super)giant stars. Probably, inhomogeneity may play important role in this transition region, and this zone may be a cool component of the chromospheric inhomogeneity such as known for the Sun(Ayres,Testerman,Brault,1986) or suggested for α Boo(Heasley et al.,1978), or a clumpy aggregation of CO cloudlets such as suggested for SiO maser region(Alcock, Rose,1986). At present,however, a detailed structure of the inner part of the circumstellar envelope is not clear at all, and the recent observations have just revealed that it is far more complicated than has been supposed before.

In this connection, one interesting suggestion is that the thermal instability due to extreme temperature sensitivity of molecular opacities induces molecular cooling and associated dynamical effect,in the outer atmosphere of red (super)giant stars (Muchmore,Nuth,Stencel,1987). Also, a possibility that molecules and dusts could be formed in a quasi-static extended chromosphere by the so-called condensation instability has been suggested from the observation that chromospheres are not completely quenched in the presence of dust(Stencel, Carpenter, Hagen, 1986). Such an idea that the formation of molecules(or dusts) could be accelerated by the thermal instability due to molecular(or dust) formation itself presents an interesting possibility for understanding the large abundance of molecules(dusts) in the outer atmosphere of cool luminous stars. Then, possible presence of the quasi-static turbulent molecular formation zone, revealed by our observations outlined in Sect.III, can be regarded as *observational evidence for such a theory of molecular(dust) formation* by *cooling(or* condensation) instability. Thus, although exact nature of the quasi-static molecular formation zone remains undefined until more detailed confrontation between theory and observation could be carried out, such an idea may have a key to understand the complicated structure of the inner part of the circumstellar envelope of red (super) giant stars, and some implications of the possible presence of such a quasi-static molecular dissociation zone in the outer atmospheres of red (super)giant stars are examined below:

(a) Structure of the Outer Atmosphere of Red Giant and Supergiant Stars

Now,with the recognition of such a new component of the outer atmosphere in cool luminous stars, the division of cool stars into two types discovered by Linsky and Haisch(1979) can be contrasted more clearly: While hot transition layer and hot corona such as known in solar type stars do not exist in red (super)giant stars, *rather cool transition layer may exist instead in red (super)giant stars. This* transition layer in noncoronal type stars can also be regarded as a cool corona extended by the turbulent pressure, just as the hot corona in solar type stars is extended by the thermal pressure. However, it should be remembered that the concept of "transition layer" or "corona" does not ncessarily imply a homogeneous structure, as is also known for the case of the Sun(for example, coronal hole). Probably, the quasi-static turbulent layer or cool corona may exist in all the red giant stars of the noncoronal type defined by Linsky and Haisch(1979), but it may be difficult to be recognized in K and early M giants, simply because optical thickness of the CO layer is too small in these stars. In red supergiant stars,the presence of rather extensive CO absorption layer is already evident in early M supergiants such as α Ori and μCep(Tsuji,1987b),and this fact implies that the quasi-static molecular layer can be formed more easily in stars of the higher luminosity at the same spectral type.

Now, if the presence of the quasi-static molecular formation zone is a fundamental property of red (super)giant stars, how could we understand the origin of such a component in outer atmosphere? One interesting possibility is that the molecular zone in outer atmosphere could be formed by the cooling instability(Muchmore,Nuth,Stencel, 1987) or by the condensation instability(Stencel,Carpenter,Hagen,1986), as noted above. Even if such a process could trigger the molecular formation in the outer atmosphere, however,there may still be two major problems: how matter can be supplied to the outer static layer and how it can be supported in the non-expanding envelope? For the first problem, we have no answer at present but we only notice that the surface gravity in red (super) giant star is much smaller than that in the Sun, in which matter can anyhow be transferred to the hot corona from the photosphere,despite the large surface gravity. In this connection, it may be interesting to remember that we have already seen upflow and downflow motions in the chromosphere(Sect.II) and such a process may be transporting the matter from the photosphere to the quasi-static molecular formation zone. For the second problem, we may suggeste that the turbulence may be important, since turbulent velocity in the CO absorption layer turns out to be actually rather high(Sect.III). At present, however,origin of stellar turbulence is not well understood,too.

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(b) Circumstellar Chemistry

Now, once the rather cool turbulent molecular formation zone or molecular condensation is formed in the outer atmsphere of red giant stars, it may have further important effects upon the chemistry of the outer atmosphere of these stars. Most importantly, the rather high gas density due to a quasi-static character and to the large scale height of the turbulent zone provides the necessary conditions for the formation of various molecules. This fact may also be important for molecular formation triggered by the cooling instability noted above. In fact, if matter is always moving outward with velocity v, gas density at radius r falls as $v^{-1}r^{-2}$. Then it may be difficlut to understand the presence of molecules in circumstellar envelope, since molecules formed in stellar photosphere should have been destroyed in passing through the warm extended chromosphere(Hartmann,1983), and formation of new molecules may be difficult at low density of the expanding envelope. In fact, the presence of a static molecular formation layer had to be assumed at the base of expanding envelope, either implicitly(Scalo,Slavsky, 1980) or explicitly(Clegg, van IJzendoorn,Allamandole,1983),in discussing circumstellar chemistry in expanding outer envelope.

We now find observational evidence for the presence of such a molecular formation zone in the quasi-static turbulent zone. From the CO column density of $10^{20}/cm^2$ (Sect.III) and the pressure scale height comparable to stellar radius of 10^{13}cm(due to large turbulence), the CO number density may be as high as $10^{7}/cm^{3}$ and this implies that the hydrogen number density should be as high as $10^{11}/cm^{3}$. Thus, molecular formation in the quasi-static turbulent layer can follow chemical equilibrium as a first approximation, and some examples of such equilibrium molecular formations were given elsewhere(Tsuji,1986b). Also, it is to be noted that the clear contrast between oxygen-rich and carbon-rich chemistries still prevails in observed circumstellar molecules(e.g.,Zuckermann,1980; Olofsson,1985),and this fact can be regarded as an evidence that the chemical equilibrium is realized approximately for the molecular formation in the inner part of the circumstellar envelope. Thus, prediction based on a chemical equilibrium can be used as an initial condition for non-equilibrium molecular formation in an expanding envelope.

(c) A Possibility of Turbulence-Driven Wind and Mass-Loss

The situation is the same for dust formation as for molecular formation: the turbulent molecular dissociation zone could provide density high enough and, at the same time, temperature low enough for dust to be formed. Thus, we now find an observational clue as to the place where dusts could be formed, to initiate mass-loss outflow. In this connection,it is interesting to remember that the strongest correlation of mass-loss rate with any of the observed properties was with the CaII K4 absorption width, and this fact may indicate that turbulence could contribute to mass-outflow by increasing the scale height of the outer atmosphere and by raising more material to the layer where the dust could be formed(Hagen, Stencel, Dickinson, 1983). However, it is not sure if the process of dust formation followed by mass outflow is a steady process. It is also possible that the dust could not be formed until the gas density of the transition layer exceeds certain critical value by the transport of the matter from the photosphere,and hence mass-outflow may be sporadic. Such a possibility is consistent with the presence of multiple expanding CO envelopes around red (super)giant stars(Bernat,1981), as noted in Sect.III.

Despite the observational identification of a possible site of dust formation, however, the dust-driven wind could not be applied to stars without dust envelope, as noted in Sect.II. Then, a more interesting possibility is a turbulence-driven wind,in which the high turbulent pressure of the transition layer(or cool corona) pushes the gas out of star,just as the high thermal pressure in corona does in solar-type stars. In fact, if the turbulent zone is extended to about 10 stellar radii, the local escape velocity there may already be small enough to be comparable with the observed flow velocities. Thus, the Maxwellian tail of the turbulent motion in the quasi-static molecular formation zone can directly lead to stellar mass-loss in all

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the noncoronal stars. The mass-loss rate -CaII K4 absorption width correlation(Hagen, Stencel,Dickinson,1983) noted before can also be regarded as supporting evidence for the turbulence-driven wind. If such a mechanism could work in cool luminous stars, dust is not necessarily the prime mover of mass-loss, but rather it is only a result of mass-loss. For example, dust could most easily be formed when gas is rapidly cooled at the sonic point during the outflow. Then dust will play only secondary role in accelerating the outflowed gas further. The relative importance of the two major possibilities, the turbulence-driven wind or the radiation-driven wind, should still be examined in detail.

V. Concluding Remarks

Recent developments of molecular spectroscopy in the infrared and radio wavelength regions made it possible to probe the cool components of the huge outer envelope of red (super)giant stars,extending from the region near the stellar photosphere ($r \sim R_* \sim 10^{13}$ cm) out to the region where the stellar wind interacts with the ambient interstellar matter($r \sim 10^5 R_* \sim 10^{18}$ cm). Our present picture is that there should be a quasi-static turbulent molecular formation zone, in the inner part of the huge expanding circumstellar envelope, possibly as an inhomogeneity in extended chromosphere or in cool corona. Presence of such a molecular formation zone in the outer atmosphere is consistent with the recent theory of molecular formation by the thermal instability due to molecular cooling(Muchmore, Nuth, Stencel, 1987). Thus, with the quasi-static molecular formation zone, observation and theory consistently show a new possibility for understanding the physics and chemistry in outer atmosphere of cool luminous stars. Also, such a new component in the inner part of the circumstellar envelope may have a key to understand the nature of huge expanding molecular envelope which show complicated velocity and spatial structures, as revealed by the recent infrared and radio observations.

Further, we suggested a possibility that the turbulence-driven wind from the quasi-static intermediate zone could provide a unified understanding of stellar mass-loss in red (super)giant stars. However, this does not solve the problem yet, but the difficulty of mass-loss mechanism is simply reduced to the problem of the origin of stellar turbulence. In this connection, it is to be remembered that one of the major unsolved problem in the theory of stellar atmospheres is how to understand the origin of stellar turbulence(e.g.,Gray,1978). Further, turbulence may already play an important role in determining the physical structure of the photosphere of cool luminous stars(de Jager,1980). We now suppose that the turbulence may play similarly important role in the stellar outer atmosphere, as it does in photospheres of cool liminous stars. Thus, fundamental problems in stellar photospheres as well as in outer atmospheres could not be deemed resolved until the origin of stellar turbulence is well understood.

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