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On the Thermal Regime and Density in the Star-Forming Regions

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Abstract

We developed an automatic code to determine some physical parameters describing the radiation of a simple one-temperature black body model and implemented it to calculating the temperatures and masses of molecular clouds in several star formation regions, using the observed IR emission fluxes for the chosen sources. Calculations show that the used commonly simplifications need to study in more detail for estimating the accuracy of computing results.

Keywords: *radiative transfer – infrared: ISM - ISM: molecular cloud*

1. Introduction

Modern stellar cosmogony adopted the idea that stars in our Galaxy (and in other galaxies) form in the cold and dense cores of giant molecular clouds. In any case, the physical connection between new formed stars and molecular clouds is obvious from observations. It is also evident that the star formation process has a recurrent behavior, and takes place several times during the galaxy lifetime. Therefore, the statement that star formation is an ongoing process, which continues in our epoch has been accepted (Ambartsumian, 1947).

The majority of adherents of the modern stellar cosmogony do not accept all the concepts put forward in Ambartsumian (1947) classical paper. Moreover, the scientific community does not retain these ideas and one can find some mentions of them, if any, in comprehensive reviews of the field. Usually authors refer these ideas as having only historical significance.

We do not consider here any conceptual issues concerning the origin of molecular clouds. Actually, the traditional cosmogony considers the molecular clouds as the direct inherent of the matter formation process due to the big bung event. Ambartsumian was not a supporter of the Universe formation owing to the single explosion of the physical vacuum. According to his vision, we have no adequate knowledge and research tools to reach the very beginning our baryonic Universe. His concept limits our mental speculations to times to which physical extrapolations are still able of giving more or less confident results. Therefore, his concept of the matter structure states only that all the existing cosmic objects have been formed thanks to the decay of much more dense matter.

In his paper "On the Origin of Nebulae" (Ambartsumian, 1982) the author mentions that the origin and evolution of stars always draws the attention of astrophysicists. However, states the author, the problems of the origin and evolution of researchers considered much less.In the paper the author takes up two different, at first glance, types of links between nebulae and stars. In the case of nebulae linked to individual stars, there is no doubt, that the stars ejected the matter to form the surrounding nebulae. The situation is more complicated when diffuse nebulae are considered. The author mentions his deep impression due to the observational facts arguing in favor of existing several diffuse nebulae within each OB stellar association. He also repeats the conclusion he made based on the given data,

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stating that generation of a group of young stars takes place parallel with the formation of surrounding them diffuse nebulae.

Sometimes researchers use the observational fact that young stars are embedded in the diffuse molecular clouds to argue their origin from nebulae. Considering all the observational data available the author arrives at a conclusion that the large nebulae located within the OB associations are in the process of mass growth, and that their mass is growing owing to the mass ejection from the objects embedded deep in the nebulae.

Although, the issue we are going to discuss here does not depend on the physical mechanism of the nebulae formation, nonetheless this brief introduction into the subject seems to be essential. It gives some information on the alternatives existing on the molecular clouds possible formation, which is usually ignored considering this subject.

In this paper, we are going to describe the computational method we used to calculate the temperature and mass of the cold dust in the star formation regions using the SED in the IR range of radiation. Method is developed and used by other researchers and we applied it for our sample only. However, its application and especially results of calculations led us to some conclusions that we would like to share here.

2. Used method and interpretation

We tried to find some physical characteristics of IR sources using simplest relations between the energy source, which provides the radiation field, and the scattering medium through which the energy transfers. This is a classical radiative transfer problem, which requires the determination of the source function. Usually, the radiation flux emerging from any emitting area is given by the following simple formula:

$$F_\nu = \oint d\omega \int_0^{\tau_0} I_\nu(\tau_\nu) e^{-\tau_\nu} d\tau_\nu, \tag{1}$$

where the first integral (in very simplified model) can be calculated immediately and shows the solid angle corresponding to the source of radiation, $I_\nu(\tau_\nu)$ is the radiation intensity at the optical depth τ_ν. Intensity depends on the temperature through the optical depth. It is obvious, that this dependence can be determined only solving the equation of the radiation transfer.

In the first approximation, one can disregard the dependence on the optical depth and substitute the intensity for the blackbody radiation for some average temperature. Then one can obtain the following relation:

$$F_\nu = \Omega B_\nu(T_d)(1 - e^{-\tau_{0_\nu}}), \tag{2}$$

where Ω is the solid angle corresponding to the given source, $B_\nu(T_d)$ is the Planck function for the dust temperature T_d and τ_{0_ν} is the optical thickness of the dust column in the radial direction. This simple formula, easy for application,has been in usage for rather long time.

Observations provide the real flux F_ν, therefore, one can use the relation 2 for determination the dust temperature and optical thickness. There are two quantities to be determined using any method of fitting, namely, the temperature T_d and optical thickness τ_{0_ν}. Both these quantities define the frequency dependence of the observed flux, but not its absolute magnitude. Therefore, one can normalize the flux values constructing the ratios

$$\eta_\nu = F_\nu / F_{\nu_1}, \tag{3}$$

where for ν_1 one can use the lowest observed frequency.

The observational quantities should fit the same quantities calculated using the model for some value of temperature. We used very simple algorithm when searching the best fitting temperature. The following sum is calculated for different temperatures:

$$\Delta(\eta) = \sum_{\nu_i} (\eta_{obs} - \eta_{mod})^2, \tag{4}$$

to find the temperature which makes the difference minimal. We used an iterative procedure of progressive approximation. In order to fulfil the procedure we started calculations with the given initial temperature T_0. After calculating the value $\Delta(\eta)$ we put $T = T + \delta T$ and find the value $\Delta(\eta)$ again. If the new value is smaller than the previous one we continue the procedure after the next increment of the argument. On the other hand, if in any step of this procedure the value $\Delta(\eta)$ increases, the special program compiled for this procedure makes the following substitution $\delta T = -\delta T/2$ and continues calculations. This procedure continues to satisfy the inequality $|\delta T| \leq \varepsilon$, where ε is the accuracy for computing the temperature.

Second physical parameter to be determined within this framework is the optical thickness of the cold dust cloud, defining its mass on its turn. Therefore, all the procedure described above we fulfilled for various values of the optical thickness. As a result, the computing program provides a set of temperature values satisfying our requirement of fitting conditions.In the final stage of the procedure computer chooses the lowest value from the set and issues the corresponding physical values.

The optical thickness of the absorbing cloud has the following form (Hildebrand, 1983):

$$\tau_{\nu_0} = \mu_{H_2} m_H K_\nu N(H_2), \tag{5}$$

where μ_{H_2} is the mean molecular weight (adopted to be 2.8 here to take into account the relative mass abundance of helium equal to 25%), m_H is the mass of hydrogen atom, K_ν is the opacity coefficient and $N(H_2)$ is the hydrogen column density. Here the frequency dependence of the opacity coefficient has the following form $k_\nu = k_0(\nu/\nu_0)^\beta$, where $k_0 = 0.1\,cm^2\,g^{-1}$ at the frequency $\nu_0 = 1200\,GHz$ ($250\,\mu m$) for a gas-to-dust ratio of 100 (André et al., 2010, Hildebrand, 1983). In Beckwith et al. (1990) is stated that the equity $k_0 = 0.1\,cm^2\,g^{-1}$ is correct at the frequency $\nu_0 = 1000\,GHz$ ($300\,\mu m$). Usually, authors put $\beta = 2$ to reduce the number of free parameters and facilitate the fitting process.

3. Numerical Results

We implemented the computational program verified using model calculations for finding the temperature and mass of molecular cloud for several IR sources. We used FIR data in the range $70 - 500\,\mu m$, obtained through *Photodetector Array Camera and Spectrometer* (PACS, Poglitsch et al., 2010) and the *Spectral* and *Photometric Imaging Receiver* (SPIRE, Griffin et al., 2010) operating at the *Herschel Space Observatory* Pilbratt et al. (2010).

For our analysis, we used photometric data and images of *PACS* 70, 160 μm catalogue and the *Herschel Infrared Galactic Plane Survey* (Hi-GAL, Molinari et al., 2016) in 70, 160, 250, 350 and 500 μm wavebands. Not all the sources have measured data in all wavebands. For the ultimate calculations, we excluded data related to the emission at the wavelength 70 μm. Therefore, all the calculations are implemented for four or less wavelength bands.

In the Table 1 we present results of the numerical calculations as an illustration. In the first column is given the radius of a source in arcseconds, the columns (2)-(5) represent here the measured fluxes in the bands 160, 250, 350 and 500 μm correspondingly. Last four columns show the temperatures and masses of the gas we received from our computations. Both values are computed using slightly different algorithms. As we described above we repeated the calculations for revealing the temperature for various values of the optical thickness for the given source. Owing to this procedure, we find different temperatures which correspond to the given optical thickness and various values of the accuracy $\Delta(\eta)$. Calculations show that the dependence of $\Delta(\eta)$ on optical thickness is not trivial as it could be if all the physical suggestions are correct. One can reveal several minima of the value $\Delta(\eta)$, which makes the selection of the optical thickness and corresponding temperature problematical. In order to smooth the mentioned dependence we used averaging of $\Delta(\eta)$ values. Therefore, we have two sets of temperature, which are shown in columns (6) and (8). The columns (7) and (9) represent masses derived from the dust emission using the relation

$$M = (d^2\Omega/k_{300})\tau_{300}, \tag{6}$$

where $k_{300} = 0.1\,cm^2\,g^{-1}$ is the opacity per unit mass computed at $300\,\mu$m assuming a gas-to dust ratio of 100 (Beckwith et al., 1990), and d = 7.8 kpc.

Table 1. Results of the numerical calculations

R (arcec) (1)	$\mathbf{F}_{160}$ (2)	$\mathbf{F}_{250}$ (3)	$\mathbf{F}_{350}$ (4)	$\mathbf{F}_{500}$ (5)	**T (K)** (6)	**M (sol)** (7)	$\mathbf{T}_{aver}$ **(K)** (8)	$\mathbf{M}_{aver}$ **(sol)** (9)
14.7	937.35	3010.82	1716.84	1629.68	7.7	8.4	10.2	11.2
30.5	1271.52	0.00	3040.54	0.00	10.2	23.2	10.2	23.2
8.4	2371.00	7223.45	3121.39	1510.98	9.3	5.9	9.4	5.9
12.3	4257.00	6153.49	3053.85	1118.18	10.3	9.4	10.2	9.4
9.9	2788.00	3628.48	0.00	3147.02	11.9	8.8	11.9	8.8
12.1	6876.00	11696.93	5084.87	3014.18	10.3	9.2	9.7	8.8
9.6	5572.00	10381.26	7172.18	3606.51	11.4	8.2	11.5	8.3
6.9	1469.00	1180.27	844.96	0.00	15.7	8.1	15.7	8.1
8.7	1351.00	1138.02	501.87	0.00	15.0	9.8	15.0	9.8
14.5	2793.00	12439.93	6148.01	1767.46	14.4	15.6	14.4	15.6
8.4	3140.00	5700.70	3425.12	1783.12	11.3	7.1	11.3	7.1
14.9	5308.00	5009.48	3110.22	1645.09	14.8	16.4	14.8	16.4
14.3	1694.97	7368.99	4367.79	3490.74	7.8	8.3	7.8	8.4
16.7	2125.46	7673.70	4149.23	2557.88	8.5	10.6	8.5	10.7
18.8	1533.75	4725.34	0.00	1003.04	8.9	12.4	8.9	12.5
27.8	934.36	10306.26	10680.46	3829.32	6.9	14.4	6.9	14.4
18.5	579.64	3898.39	2849.43	1163.10	7.5	10.4	7.5	10.4
12.4	3149.00	4762.17	2694.73	1326.15	12.2	11.4	12.3	11.4
13.8	1722.67	8057.09	2346.18	893.03	8.5	8.8	8.5	8.8
15.1	3302.00	5743.38	3968.28	3529.04	11.6	13.1	11.6	13.1
16.9	1645.74	2761.04	3382.35	1156.78	11.0	14.0	11.0	14
8.9	2863.00	5841.19	2304.80	1572.25	10.1	6.7	10.0	6.6
10.0	2703.00	4276.10	2771.28	0.00	11.9	8.9	11.9	8.9
12.0	5140.00	3884.68	1783.74	0.00	16.7	14.9	16.5	14.8
12.3	3218.94	7620.25	3339.08	0.00	9.6	8.8	9.6	8.8
12.0	21103.00	13614.83	5797.80	0.00	18.2	16.3	18.2	16.3
13.1	18514.00	17472.91	6755.87	0.00	12.8	12.5	12.9	12.7
10.8	9397.00	10449.92	5174.50	0.00	12.7	10.3	13.3	10.8
9.4	1734.00	2285.95	2686.00	0.00	11.9	8.4	11.9	8.4
9.9	1812.00	4627.39	6037.34	0.00	9.7	7.2	9.7	7.2
11.5	4086.00	7347.94	0.00	0.00	11.4	9.9	11.5	9.9
10.5	1546.00	3507.15	2058.25	1669.82	11.0	8.6	11.0	8.6
10.6	1145.00	1469.08	2176.42	0.00	11.5	9.1	11.5	9.1
13.1	2469.99	3383.57	1813.73	0.00	11.8	11.6	11.7	11.5
19.0	749.66	2358.91	1447.72	0.00	8.9	12.6	8.9	12.7
16.8	1571.04	3423.60	1650.72	0.00	10.0	12.5	10.0	12.5
11.3	1868.00	2175.02	1049.56	0.00	11.0	9.3	11.4	9.6
15.4	3796.00	4828.40	1675.96	0.00	11.5	13.2	11.7	13.4
13.4	5570.00	9360.75	4957.03	1239.90	10.4	10.5	10.8	10.8

4. Discussion

Calculations show that the physical picture of the process is more complicated than researchers consider for studying it. Actually, all the attempts used for modelling the process going on in the molecular clouds are extremely simplified. There are two main suggestions used by researchers, simplifying the situation. First assumption facilitating the model is one that the intensity does not depend on the optical depth. Undoubtedly, this is not correct, but the general solution of the problem makes its usage very uneasy. The second one, in our opinion, is replacement of the intensity in the relation 1 by a one temperature Planck function. These simplifications led to some uncertainties, which show up during the procedure of the temperature determination.

We have no any theoretical recipe for overcoming this situation. However,we are going to study the problem in more detail to reveal at least which simplification is rougher and how big can be errors using it.

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