Studying the Atomic and Molecular Hydrogen Mass (MHI, MH₂)
Properties of the Extragalactic Spectra

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Received: 5/8/2019 Accepted: 30/9/2020

Abstract
The purpose of this study is to deal with dust and interstellar molecular and atomic gas owing to obtaining a proportion of cold gas to dust and to understand the characteristics of the molecular gas in extragalactic data selected from the Herschel SPIRE/FTS archive. The physical properties of a sample of 65 extragalactic spectra characterized by the activity of star formation were discussed in this work. Statistical analyses, using STATISTICA program, were made for the content of cold gas (MHI, MH₂), dust mass (M_dust), cold temperature of dust (T_d) and luminosities in Far-infrared to CO line radiations, while coefficients of partial correlation within those characteristics were established. The results showed that the molecular hydrogen mass (MH₂) is strongly correlated with the HI or the total gas mass corresponding to the Far-infrared emission (L_FIR) resulting from dust in the galaxies molecular clouds. The results also indicated that these kinds of galaxies have large molecular mass as well as high star formation efficiency per unit mass.

Keywords: Galaxies; Interstellar gas; Molecular clouds; Far-Infrared and CO line radiations.

دراسة خصائص كتلة الهيدروجين الذري والجزيئي (MH₂, MHI) لأطياف المجرات الخارجية

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الخلاصة
ان الغرض من هذه الدراسة هو التعامل مع الغبار والغازات الجزيئية والذرية ما بين النجوم وذلك للحصول على نسبة الغاز البارد إلى الغبار وفهم خصائص الغاز الجزيئي من بيانات المجرات الخارجية المختارة من في هذا العمل تميز مرحلة الفيزيائية لعينة 65 من أطياف المجرات الخارجية والتي تميز بفعالية النشوء الجماعي. تم إجراء الدراسات الإحصائية لمجموعة من مساحات الأشعة تحت الحمراء (MHI, MH₂) ودرجة الحرارة الباردة للغاز (T_d) وكتلة الغبار (M_dust) ودرجة الحرارة الباردة للغاز (L_FIR). النتائج أظهرت أن كتلة (MH₂) مترابطة ارتباطًا قويًا مع كتلة الهيدروجين الذري HI أو كتلة الغاز الكلي المقابلة (MHI) أو كتلة الهيدروجين الجزيئي (MH₂) لانبعاثات الأشعة تحت الحمراء البعيدة (L_FIR) الناتجة من الغاز الموجود في السحب الجزيئية للمجرات. بالإضافة إلى أن هذه الأنواع من المجرات تمتلك كتلة جزيئية كبيرة إضافة إلى كفاءة تكوين نجمي عالية لكل وحدة كتلة.

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Introduction

Galaxies throughout all environments can possess a cold gas component suitable for powering star formation or an active galactic nucleus (AGNs). Studies of local universe galaxies demonstrated that many of them contain important nuclear and molecular cold gas reservoirs [1]. The molecular gas within the multi-phase interstellar medium (ISM) was the most closely tied to star formation rate (SFR), and thus dramatic effects on galaxies evolution are associated with the stellar lifecycle. Even if the dominant component of such gas is molecular hydrogen (H2), it is difficult to detect pure H2 rotational lines without being especially sensitive to the cold temperatures of most molecular clouds [2]. The star formation efficiency (SFE) is a crucial component in understanding the history of star formation of galaxies at all redshifts as well as the universe’s global evolution [3].

The poor understanding of the physical principles behind the star formation process still restricts our knowledge of galaxies evolution, in other words, the condensation of the primitive gaseous material of HI into H2 and thus its collapse into stars. The feedback mechanisms caused by the recently born stars on the ISM are also poorly known. The ultraviolet emission field (UVWF) linked with massive star formation causes the nearby gas to be ionized and leads the hydrogen molecules to be photo-dissociated. Supernova winds, furthermore, inject kinetic energy (and metals) into the ISM, causing unique star formation on the shock wave fronts [4]. Far-infrared radiations in these sources are primarily caused by ultraviolet (UV) emission-warmed dust from young and gigantic stars in the neighbor galaxies [5]. A previous study [6] illustrated that massive envelopes of extragalactic emission’s ionized hydrogen (HII) with masses that are significantly surpassing the masses of intergalactic HI disks could exist across galaxies in which the dimensions of HI disks exceed those of stellar disks considerably. These enlarged disks could in considerable time scales "feed" the formation rate of stars in their host galaxies. According to a published article [7], the nuclei of active galaxies that are contiguous to molecular gas tend to have considerably redder infrared colors and they cause a lack in molecules of carbon monoxide (CO) detections, revealing duster environments in the CO luminous nuclei.

Evolution observations in the dust-to-metal ratio enable us to restrict the processes of the prevailing dust processing [8]. The forms of HI H2 are well linked with previous and present indices of star formation rate, such as the brightness of the surface of the blue F	extsubscript{B}, Far-infrared F	extsubscript{FIR} and radio continuum F	extsubscript{R}, but the correlation is stronger for the molecular clouds content of MH2 [9], indicating increased molecular hydrogen gas excitation. Findings related to the dust and the atomic and molecular gas mass of these galaxies enable us to investigate their star formation activity and obtain their interstellar gas properties.

This paper is structured according to the following: We describe the characteristics of our observational data details of the 65 extragalactic samples and procedures to evaluate all parameters in Section 2. The results and discussion of our statistical analysis are presented in Section 3. The conclusions drawn from this study are given in Section 4.

**Observations Sample and Description Parameters**

**Sample Selection**

The cold gas (atomic + molecular) kinematics for 65 extragalactic spectra samples from an archive of the Herschel SPIRE Fourier Transform Spectrometer (FTS) were studied by means of the statistical analysis of the MH2+HI masses properties. In particular, cold gas masses-to-luminosities relations of SPIRE observations of the galaxies were studied extensively. The limited parameters (for example; galaxy name, Far-infrared luminosity L	extsubscript{FIR} and distance luminosity D	extsubscript{L}) were extracted from new observations of a recent paper [2], while the redshifts of galaxies measured by Doppler-shifted (z), Far-infrared fluxes at 60 μm and 100 μm (F	extsubscript{60} and F	extsubscript{100}) were taken from NASA/IPAC Extragalactic Database (NED) [10]. The calculated parameters (name galaxy, Log L	extsubscript{FIR}, D	extsubscript{L}, z, F	extsubscript{60}, and F	extsubscript{100}) of each selected galaxy are listed in Table-1.
Table 1 - Data obtained from [2] and NASA/IPAC Extragalactic (NED) of the parameters used in our analysis.

| No. | Name Galaxy     | $\log L_{FIR}$ ($L_\odot$) | $D_l$ (Mpc) | $z$ | $F60$ (Jy) | $F100$ (Jy) | Morphological Type |
|-----|-----------------|----------------------------|-------------|-----|------------|------------|-------------------|
| 1   | NGC 0023        | 10.9                       | 68          | 0.01524 | 9.03       | 15.66      | Sa                |
| 2   | NGC 34          | 11.2                       | 85          | 0.02000 | 17.05      | 16.86      | S0-a              |
| 3   | IRAS 00188-0856 | 12.2                       | 591         | 0.12800 | 2.592      | 3.403      | Galaxy or QSO    |
| 4   | ESO 350-IG038   | 10.8                       | 87          | 0.02100 | 6.88       | 5.04       | Irr               |
| 5   | IRAS 00397-1312 | 12.6                       | 1285        | 0.26100 | 1.832      | 1.904      | Galaxy or QSO    |
| 6   | NGC 0232        | 11.2                       | 95          | 0.02300 | 10.05      | 15.75      | S0               |
| 7   | NGC 253         | 10.3                       | 3           | 0.00100 | 967.81     | 1288.15    | SBa               |
| 8   | I Zw 1          | 11.4                       | 272         | 0.06000 | 2.161      | 1.749      | Sc                |
| 9   | NGC 0317B       | 11                         | 80          | 0.01771 | 9.34       | 13.95      | SBBc              |
| 10  | IRAS 01003-2238 | 11.9                       | 539         | 0.11800 | 2.287      | 1.79       | Galaxy or QSO    |
| 11  | IC 1623         | 11.4                       | 86          | 0.01900 | 23.85      | 31.53      | S?                |
| 12  | ESO 244-G012    | 11.1                       | 95          | 0.02290 | 9.27       | 11.76      | Sc                |
| 13  | CGCG 436-030    | 11.5                       | 138         | 0.03100 | 10.71      | 9.67       | Sbc               |
| 14  | Mrk 1014        | 12.3                       | 763         | 0.16300 | 2.348      | 1.915      | Galaxy or QSO    |
| 15  | NGC 0828        | 11.1                       | 80          | 0.01792 | 11.46      | 25.33      | Sa                |
| 16  | NGC 0891        | 10.2                       | 10          | 0.00176 | 66.46      | 172.23     | Sb                |
| 17  | UGC 01845       | 10.9                       | 70          | 0.01514 | 10.31      | 15.51      | Sab               |
| 18  | NGC 0958        | 10.9                       | 82          | 0.01915 | 5.85       | 15.08      | SBc               |
| 19  | NGC 1056        | 9.7                        | 24          | 0.00515 | 5.33       | 10.2       | Sa                |
| 20  | NGC 1097        | 10.4                       | 16          | 0.00424 | 58.29      | 116        | SBB              |
| 21  | IRAS 03158+4227 | 12.4                       | 623         | 0.13400 | 4.256      | 4.276      | Galaxy or QSO    |
| 22  | 3C 84           | 10.8                       | 78          | 0.01756 | 7.09       | 7.6        | S0                |
| 23  | NGC 1482        | 10.5                       | 25          | 0.00620 | 33.36      | 46.73      | S0-a              |
| 24  | IRAS 03521+0028 | 12.3                       | 709         | 0.15191 | 2.638      | 3.833      | Galaxy or QSO    |
| 25  | UGC 02982       | 10.9                       | 77          | 0.01771 | 8.38       | 16.82      | SABa              |
| 26  | ESO 420-G013    | 10.7                       | 49          | 0.01191 | 13.66      | 20.88      | S0-a              |
| 27  | NGC 1572        | 11                         | 86          | 0.02039 | 8.03       | 16.81      | Sbb               |
| 28  | NGC 1614        | 11.3                       | 68          | 0.01600 | 32.12      | 34.32      | Sbc               |
| 29  | UGC 03094       | 11.1                       | 108         | 0.02470 | 6.35       | 12.85      | Sab               |
| 30  | MCG-05-12-006   | 10.9                       | 78          | 0.01875 | 8.15       | 9.404      | SBb               |
| 31  | IRAS F05189-2524| 11.8                       | 185         | 0.04256 | 13.25      | 11.84      | E                 |
| 32  | IRAS09022-3615  | 12                         | 411         | 0.05960 | 11.64      | 11.08      | Galaxy or QSO    |
| 33  | NGC 2764        | 10                         | 40          | 0.00907 | 3.67       | 7.224      | S0                |
|    |   |   |   |      |      |     |
|----|---|---|---|------|------|-----|
| 34 | M81 | 9.2 | 4 | 0.00090 | 6.806 | 32.03 | Sab |
| 35 | NGC 3077 | 7.7 | 1 | 0.00005 | 15.9 | 26.53 | S? |
| 36 | NGC 3221 | 10.7 | 61 | 0.01370 | 7.72 | 18.76 | Sc |
| 37 | IRAS F10565+2448 | 11.8 | 192 | 0.04300 | 12.1 | 15.01 | Irr |
| 38 | NGC 3627 | 10.2 | 12 | 0.00243 | 66.31 | 136.56 | Sb |
| 39 | ESO 32O-G030 | 11 | 45 | 0.01084 | 34.38 | 46.28 | SABa |
| 40 | NGC 4051 | 9.5 | 14 | 0.00234 | 10.53 | 24.93 | SABb |
| 41 | NGC 4459 | 9.1 | 19 | 0.00396 | 1.87 | 4.82 | S0 |
| 42 | NGC 4569 | 7.5 | 1 | 0.00510 | 9.8 | 26.56 | Sab |
| 43 | NGC 4710 | 9.6 | 18 | 0.00375 | 5.89 | 13.21 | S0-a |
| 44 | NGC 4736 | 9.9 | 8 | 0.00105 | 71.54 | 120.69 | SABa |
| 45 | NGC 5010 | 10.6 | 43 | 0.02100 | 10.29 | 21.69 | S0-a |
| 46 | NGC 5104 | 10.9 | 82 | 0.01855 | 6.78 | 13.37 | Sa |
| 47 | IRAS 14378-3651 | 11.9 | 303 | 0.06760 | 6.72 | 8.08 | Galaxy or QSO |
| 48 | NGC 5866 | 9.4 | 14 | 0.00225 | 5.26 | 16.98 | S0-a |
| 49 | IRAS 16090-0139 | 12.3 | 618 | 0.13400 | 3.609 | 4.874 | Galaxy or QSO |
| 50 | PG 1613+658 | 11.5 | 600 | 0.12900 | 0.635 | 1.002 | E |
| 51 | IRAS F16399-0937 | 11.3 | 118 | 0.02701 | 8.42 | 14.72 | Galaxy or QSO |
| 52 | NGC 6240 | 11.6 | 108 | 0.02450 | 22.94 | 26.49 | S0-a |
| 53 | NGC 6701 | 10.9 | 62 | 0.01320 | 10.05 | 20.05 | Sa |
| 54 | IRAS 19254-7245 | 11.8 | 270 | 0.06170 | 5.16 | 5.789 | Galaxy or QSO |
| 55 | IRAS 20100-4156 | 12.4 | 595 | 0.13000 | 5.19 | 5.165 | Galaxy or QSO |
| 56 | MCG+04-48-002 | 10.9 | 65 | 0.01400 | 8.15 | 12.5 | Sd |
| 57 | NGC 6946 | 9.8 | 5 | 0.00015 | 129.78 | 290.69 | SABc |
| 58 | IRAS 20414-1651 | 12 | 392 | 0.08600 | 4.364 | 5.247 | Galaxy or QSO |
| 59 | IC 5063 | 10.2 | 46 | 0.01130 | 5.87 | 4.25 | S0-a |
| 60 | CGCG 448-020 | 11.7 | 161 | 0.03610 | 12.65 | 11.76 | S0-a |
| 61 | NGC 7582 | 10.5 | 21 | 0.00500 | 52.25 | 82.86 | SABa |
| 62 | IRAS 23230-6926 | 12.1 | 482 | 0.10700 | 3.744 | 3.42 | Galaxy or QSO |
| 63 | IRAS 23365+3604 | 12 | 290 | 0.06450 | 7.44 | 9.01 | Galaxy or QSO |
| 64 | NGC 7771 | 11.1 | 63 | 0.01400 | 20.93 | 44.85 | Sa |
| 65 | Mrk331 | 11.2 | 81 | 0.01848 | 18.43 | 22.56 | Sa |

Note: QSO=Quasar and **Irr=Irregular galaxy; E=Ellipticals.

**Statistical procedures**

The statistical software, statistic-win-program, was utilized to process and analyze various relationships between variables and calculate whether toughness of regression exists between the behaviors of the two variables. This association is also represented in the form of scattering graphs. The linear partial correlation (R) coefficient values range from +1 to -1 [11, 12]. A regression value...
of ±1 refers that the two functions are perfectly correlated. Indeed, when the value of the measurement of R is or close to zero, there is a weak regression correlation between the two components. **Description Parameters**

In general, the term luminosity of the CO line was calculated from the integrated intensity $S_{co}$ in Jy Km s$^{-1}$, and beam solid angle $\Omega_B = \pi \theta_B^2 / 4 \ln 2$ ($\theta_B$ in radians). The CO line luminosity can be found by [13, 14]:

$$L_{co} = \frac{\Omega_B S_{co} D_l^2}{(1 + z)^3} \text{ (in K km s}^{-1}\text{pc}^2)$$  \hspace{1cm} (1)

where $D_l$ is the distance of cosmological luminosity in megaparsec (Mpc) described by standard cosmological parameters including Hubble constant $H_0$, matter density parameter $\Omega_M$, and a parameter of cosmological constant density $\Omega_\Lambda$, and can be determined by [13]:

$$D_l = \left(1 + z\right) \frac{c}{H_0} \int_0^z \frac{dz}{[\Omega_M (1 + z)^3 + \Omega_\Lambda]^{1/2}}$$  \hspace{1cm} (2)

By substituting equation (2) in equation (1), the CO line luminosity ($L_{co}$) takes the form:

$$L_{co} = \left(\frac{c}{H_0}\right)^2 \frac{\Omega_B S_{co}}{(1 + z)^3} \left[\Omega_M (1 + z)^3 + \Omega_\Lambda\right]^{1/2}$$  \hspace{1cm} (3)

where c is the speed of light.

For galaxies without strong interactions, the following relationship between $L_{FIR}$ and $L_{CO}$ is constructed by [15, 16]:

$$\frac{L_{FIR}}{10^9} L_\odot = 31 \left[\frac{L_{co}}{10^9} L_\odot\right]^{0.74}$$  \hspace{1cm} (4)

and could be written in the form:

$$\left[\frac{L_{FIR}}{10^9} L_\odot\right]^{1.35} = \left[\frac{L_{co}}{10^9} L_\odot\right]^{0.74}$$  \hspace{1cm} (5)

The logarithmic scale of equation (5) is written as:

$$\log L_{co} = 1.35 \log L_{FIR} - 5.2$$  \hspace{1cm} (6)

Here $L_{co}$ and $L_{FIR}$ are given in the solar luminosity unit ($L_\odot$).

The molecular hydrogen gas mass $M_{HI}$ in solar mass ($M_\odot$) is derived with the use of the formula [14-17]:

$$M_{HI}(M_\odot) = \alpha_{CO} L_{co}(L_\odot)$$  \hspace{1cm} (7)

where $\alpha_{CO}$ is the CO line luminosity-to- molecular gas mass conversion factor. The conversion factor $\alpha_{CO}$ is almost constant and equal to $\alpha_{CO} \approx 0.6 - 5$ in unit $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ [14-19]. The value of $\alpha_{CO}$ that is used in this study is ~ 4.8 $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ [15-17].

From equations 6 and 7, we have:

$$\log M_{HI}(\text{in unit } M_\odot) = 1.35 \log L_{FIR}(L_\odot) - 4.5$$  \hspace{1cm} (8)

The dust temperature $T_d$ in (K$^0$) is given roughly by [20, 21]:

$$T_d \approx 49 \left(\frac{F_{60 \mu m}}{F_{100 \mu m}}\right)^{0.4}$$  \hspace{1cm} (10)

where $F_{60}$ $\mu m$ and $F_{100}$ $\mu m$ are IRAS Far- infrared band fluxes at 60 $\mu m$ and 100 $\mu m$ in unit Jansky (Jy), where 1 Jy= $10^{-26}$ W.m$^{-2}$.Hz$^{-1}$ (in units SI).

The dust mass of galaxies $M_{dust}$ in the solar mass unit can be estimated by integrating the temperature database with the Far-infrared flux rates of F60 $\mu m$ and F100 $\mu m$ [20, 22]:

$$M_{dust}(M_\odot) = 0.00478 F_{100}(mJy).D_l^2 \left(\frac{2.94 \left(\frac{F_{100 \mu m}}{F_{60 \mu m}}\right)^{0.4}}{e^{2.94 \left(\frac{F_{100 \mu m}}{F_{60 \mu m}}\right)^{0.4}} - 1}\right)$$  \hspace{1cm} (11)

We can re-write equation (10) as:

$$\frac{F_{100 \mu m}}{F_{60 \mu m}}^{0.4} = \frac{49}{T_d}$$

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The substitution of the term $\frac{49}{T_d}$ instead of $\left(\frac{\nu_{100\mu m}}{F_{60\mu m}}\right)^{0.4}$ in equation (11) yields:

$$M_{dust}(M_\odot) = 4.78F_{100}(Jy)D_l^2\left(e^{1.44/T_d} - 1\right)$$ (12)

7- The star formation rate (SFR) is calculated in Far-infrared bands (60-100 μm) from the relation [23]:

$$SFR_{FIR} = \left(\frac{L_{FIR}}{5.7 \times 10^9 L_\odot}\right) \left(\text{in } M_\odot \, \text{yr}^{-1}\right)$$ (13)

8- Lifetime gas depletion ($t_{gas}$) which is usually measured in years and caused by high mass star formation (without mass recycling by supernovae or other mass losses) is calculated as follows [16]:

$$t_{gas} = 5 \times 10^{10} \left(\frac{L_{CO}}{L_{FIR}}\right) \left(\text{in unit yr}\right)$$ (14)

**Results and Discussion**

This work studied the relationships between Far-infrared, CO emission line luminosities, star formation rates in the Far-infrared band and masses of atomic hydrogen (MHI) and molecular hydrogen (MH$_2$) of a Herschel SPIRE FTS galaxies sample. The results of the comparison between the cold gas content and luminosities revealed different effects.

The results of statistical analysis showed that the mean value ± standard error of Log$L_{FIR}$ is equal to 10.93 ± 0.12 ($L_{FIR}=8.5 \times 10^{10} L_\odot$) for our sample galaxies. These galaxies have a higher Far-infrared luminosity with a lower limit of about $3.2 \times 10^{10} L_\odot$ and an upper quartile which is equal to $5 \times 10^{11} L_\odot$.

The calculations showed a very strong relationship $L_{FIR} \propto (\text{MHI+MH}_2)^{1.11 \pm 0.024}$ with a very strong positive partial correlation coefficient (R=0.98) and a very high probability level ($p \leq 10^{-7}$), where $p$ is the probability of chance correlation. Figure-1a shows that the slope is linear and steeper than unity.

This study also revealed that the total mass of cold gas (MHI+MH$_2$) and CO/FIR luminosities, along with their relative H$_2$ and HI content alone, are the factors that indicate the actual meaning of the gas.

The relationships among the logarithm dust mass, $L_{CO}/L_{FIR}$ ratio, and MHI+MH$_2$ of these galaxies were studied. The statistical analysis results showed significant relationships between (Log L$_{CO}$/L$_{FIR}$, Log M$_{dust}$) and Log (MHI+MH$_2$) with a very strong partial correlation coefficient (R=1) and a very high probability ($p \leq 10^{-7}$), where Figure-1b reveals that the slope is almost linear (Slope > 1). The $L_{CO}$ to L$_{FIR}$ ratio provides a qualitative measure of star formation activity in the interaction of galaxies, where the average value $<L_{CO}/L_{FIR}> = 0.05$. These galaxies have higher infrared luminous than CO emission. We can conclude that CO emissions will be very essential for studying the central region's gas kinematics and dynamics. Thus, the star formation rate is related to the total gas mass of galaxies.

**Figure 1** (a) Far-Infrared luminosity Log $L_{FIR}$ as a function of total cold gas (MHI+MH$_2$), in solar units. The solid line represents the linear correlation regression. (b) The relationship between dust mass of galaxies M$_{dust}$ (on the left), ratio L$_{CO}$/L$_{FIR}$ (on the right) and MHI+MH$_2$. The straight black line represents the fitting to all the data for M$_{dust}$ and the dashed line represents the fitting to the all data for L$_{CO}$/L$_{FIR}$ versus MHI+MH$_2$, respectively.
Figure-2a (left panel) demonstrates that the ratio $\log(L_{\text{FIR}}/M_{\text{H}_2})$ and dust temperature Figure-2a (left panel) demonstrates that ratio $\log(L_{\text{FIR}}/M_{\text{H}_2})$ and dust temperature ($T_d$) indicate a clear negative relationship with a correlation coefficient of $(R≈-0.46)$ and a good probability value $(p≈10^{-4})$. It should be pointed out here that the slope of the line is $= 0.42±0.09$. The value of the ratio of Far-infrared emission luminosity to molecular gas implies that the SFR strongly depends on the dust temperature ($T_d$). The significant relationship between $L_{\text{FIR}}/M_{\text{H}_2}$ ratio and $T_d$ supports essentially that the Far-infrared emission comes from the merged dust with the molecular clouds.

The mean values of the logarithmic scale of cold gas masses ($M_{\text{HI}}, M_{\text{H}_2}$) of our sample were $9.75±0.08$, $10.26±0.17$, and $7.06±0.11$, whereas those for $M_{\text{dust}}$ were $5.6x10^7 M_\odot$, $1.8x10^{10} M_\odot$, and $1.1x10^9 M_\odot$, respectively. Figure-2b (right panel) shows a linear relationship, implying that the correlation between molecules gas to dust masses and dust temperature ($\log (M_{\text{H}_2}/M_{\text{dust}})$, $T_d$) is positive and very strong $(R≈0.87)$ with a stronger probability $(p≤10^{-7})$. The used linear regression equation is given by:

$$\log M_{\text{H}_2}/M_{\text{dust}} = S T_d + m,$$

where $S$ is the slope and $m$ is the intercept with the y-axis. It should be noted that the best representation is obtained by a minimum standard error which is clarified in the form of: $
\log M_{\text{H}_2}/M_{\text{dust}} = (0.75±0.05)T_d + (1.74±0.27)$. Figure-2b (solid black line), which describes the relationship between $(\log M_{\text{H}_2}/M_{\text{dust}})$ and $(T_d)$, shows that $R≈0.45$, $p≈10^{-4}$, and the slope of the solid line is $≤ 0.5$. The comparison between the ratio $M_{\text{H}_2}/M_{\text{dust}}$ and the $T_d$ indicates that the resulted ratio varies from a galaxy to another and that the dust is regarded as an indicator of gas in its atomic and molecular forms.

This work studied the relationship between the ratio masses of molecular hydrogen to dust content ($M_{\text{H}_2}/M_{\text{dust}}$) and the Far-infrared luminosity of galaxies. The results of the statistical analysis showed a strong relationship between $\log (M_{\text{H}_2}/M_{\text{dust}})$ and $\log L_{\text{FIR}}$ with a positive and very strong correlation coefficient $(R≈0.84)$ and a higher probability $(p≤10^{-7})$. The ratio $M_{\text{H}_2}/M_{\text{dust}}$ is used as a function of the Far-infrared luminosity in Figure-3a (left panel), which demonstrates that the relationship is taking the form: $(M_{\text{H}_2}/M_{\text{dust}} \propto L_{\text{FIR}}^{0.84±0.08})$. The ratio $M_{\text{H}_2}/M_{\text{dust}}$ is also taken as a function of the dust temperature in (Figure-2b left). Both figures showed that the ratio does not depend on the type of
morphology of the galaxies, which was also confirmed by previous results [i.e. 7, 15 and 16]. Our results indicate that dust may be associated with the stars emerging in the central bulges of such galaxies, which leads to increasing the dust mass and reducing the cold gas to dust mass ratio.

The relationship between $L_{\text{co}}/L_{\text{FIR}}$ and $T_d$, as shown in Figure-3b (right panel), showed a correlation coefficient of $R \approx 0.5$, probability of $p \approx 10^{-5}$, and slope of $-0.23 \pm 0.06$. The results indicate a weak relationship, due to the effect of distance $D_l$ or redshift $z$ based on Malmquist bias (the effect of distance dependence selection) between the parameters in this sample (see equations 1 and 3).

![Figure 3](image_url)

**Figure 3-(a)** The ratio $M_{H_2}/M_{\text{dust}}$ as a function of $L_{\text{FIR}}$. **(b)** The ratio CO line emission ($L_{\text{CO}}$) to Far-infrared emission ($L_{\text{FIR}}$) luminosities as a function of $T_d$.

Now we discuss the relationship between the atomic and molecular gas to dust masses and gas depletion lifetime ($t_{\text{gas}}$). It was found that the linear regression of Figure-4a (left panel) is taking the form: $\log M_{H_2}/M_{\text{dust}} = (1.3 \pm 0.15) \ t_{\text{gas}} + (2.26 \pm 0.09)$ while for Figure-4b (right panel) it is: $\log M_{H_1}/M_{\text{dust}} = (-0.72 \pm 0.25) \ t_{\text{gas}} + (2.99 \pm 0.08)$. There is an interesting relationship between these quantities with a strong positive correlation coefficient ($R \approx 0.73$) and a very high probability ($p \leq 10^{-7}$) between $\log (M_{H_2}/M_{\text{dust}})$ and $t_{\text{gas}}$. A negative relationship between $\log (M_{H_1}/M_{\text{dust}})$ and $t_{\text{gas}}$ was also observed, with a partial correlation value of $R \approx 0.33$ and a significance probability ($p=6 \times 10^{-3}$). Based on a sample of extragalactic spectra, we show that the cold gas depletion lifetime is dependent on high star formation efficiency (SFE) with extreme $L_{\text{co}}/L_{\text{FIR}}$ ratio in these galaxies, indicating that the star formation process can only be enhanced by very strong interactions between galaxies.

![Figure 4](image_url)

**Figure 4- (a)** The ratio $M_{H_2}/M_{\text{dust}}$ versus lifetime gas depletion $t_{\text{gas}}$ in years unit. **(b)** The ratio $M_{H_1}/M_{\text{dust}}$ versus $t_{\text{gas}}$. 
In this work, we also studied the relationships between the mass dust of galaxy \(M_{\text{dust}}\) and ratio mass MHI/MH\(_2\), CO-luminosity \(L_{\text{CO}}\), star formation rate in Far-infrared band \((\text{SFR}_{\text{FIR}})\). The results showed mean values of Log MHI/MH\(_2\)= -0.51±0.09, LogL\(_{\text{CO}}\)=9.57±0.17 \((L_{\text{CO}} \approx 3.7 \times 10^{9} \, L_{\odot})\), and SFR\(_{\text{FIR}}\)= 44.25 \(M_{\odot}\) yr\(^{-1}\) for our sample galaxies. The existence of a negative correlation between MHI/MH\(_2\) ratio and \(M_{\text{dust}}\) was recorded, with a partial coefficient of \(R \approx -0.9\). For a slope \(~ -1\), we have the LogM\(_{\text{dust}}\) is inversely proportional to Log (MHI/MH\(_2\)). It can also be noticed that if the HI / H\(_2\) ratio mass is less than or equal to 1 (MHI / MH\(_2\) \leq 1), there is a systematic variation in the HI content, while the deficiency of MHI as the relative abundance of the molecular component (MH\(_2\)) increases.

The results also showed a very strong linear correlation between LogL\(_{\text{CO}}\) and LogM\(_{\text{dust}}\) with a correlation coefficient of \(R=0.92\), a very strong probability \((p \leq 10^{-7})\), and a Slope \(~ 0.86\pm0.04\). In terms of statistics, we deduce a tight linear relationship between \(M_{\text{dust}}\) and \(\text{SFR}_{\text{FIR}}\) (Slope \(~ 1\)). For these galaxies, star formation rate in the Far-infrared radiation band \((\text{SFR}_{\text{FIR}})\) is strongly related to their dust content, which is relevant for galaxies involving a wide range of the FIR luminosity. We also found a statistically significant relationship with a clear positive correlation between these parameters \((R=0.5)\), with a good probability level \((p=2\times10^{-5})\). In Figures-(5a, 5b) and 6, we examine the LogM\(_{\text{dust}}\) versus Log MHI/MH\(_2\), LogL\(_{\text{CO}}\) versus LogM\(_{\text{dust}}\), and \(M_{\text{dust}}\) versus \(\text{SFR}_{\text{FIR}}\), respectively. The MH\(_2\) derived from the CO surface brightness is more strongly linked with the \(M_{\text{dust}}\) than the MHI surface mass, however, the dust mass association of the molecular content is not significant. Therefore, cold dust emission is probably correlated with both of the atomic and molecular forms in these galaxies. In fact, the dust mass is often related to the MHI+MH\(_2\). Our findings from this analysis are consistent with those of previous articles [7, 9, 15, 16].

**Figure 5**-(a)The \(M_{\text{dust}}\) \((M_{\odot})\) as a function of the ratio MHI/MH\(_2\). (b) The CO line luminosity versus \(M_{\text{dust}}\), on a scale of logarithms.

**Figure 6**- The mass dust \(M_{\text{dust}}\) versus star formation rate in \((M_{\odot} \, \text{yr}^{-1})\).
The results of regression analysis show that the logarithmic ratio of $L_{\text{FIR}}/M_{\text{H}_2}$ to $F_{100}/F_{60}$ is apparently positive and well correlated ($R \sim 0.5$) and that their relationship is not linear ($L_{\text{FIR}}/M_{\text{H}_2} \propto F_{100}/F_{60}$ $^{0.4 \pm 0.06}$, as demonstrated in Figure-7a (left panel). This indicates that the Far-infrared luminosity for each unit of the molecular gas mass is an indicator of the star formation rate as it is directly related to infrared luminosity, where star formation activity occurs within the molecular clouds as an indication of the cold dust temperature component (which is mainly mixed with the HI gas). The parameter log ($F_{100}/F_{60}$) is introduced because the real situation is more complicated and because it provides a reliable indication of the dust temperature between 26.37 K and 55.76 K which is based on the power-law emission adopted (i.e. $B_\lambda \propto \lambda^n$, with $n=0$).

Figure-7b (right panel) reveals the variation of the cold dust temperature with the parameter ($F_{100}/F_{60}$). These results are consistent with previously reported findings [1].

**Figure 7**- (a) The relationship between ratio $L_{\text{FIR}}/M_{\text{H}_2}$ in (L$_{\odot}$/M$_{\odot}$) and the flux ratio $F_{100}/F_{60}$. (b) The cold dust temperature $T_d$ (K)$^0$ as a function of ratio $F_{100}/F_{60}$ for n=0.

**Conclusion**

On the basis of our statistical analysis, we infer that the molecular and atomic hydrogen contents are related to a linear relationship (Slope $\sim 1$) with the hotter dust mass, but the correlation in the case of molecular gas is stronger. This refers to the abundance of dust in the case of atomic and molecular gas produced in the Far-infrared wavelengths band (60 -100$\mu$m). We found, based on the statistical analysis, that the average value of the ratio $M_{\text{H}_2}/M_{\text{dust}}$ is 1.8x10$^{10}$ M$_{\odot}$. The results also indicated that far-infrared emission has a tight relationship with all variables, which illustrates the presence of recent starburst which is in turn an indicative of the star formation activity, as Far-infrared luminosity ($L_{\text{FIR}}$) is related with the mass of molecular hydrogen and star formation rate (SFR$_{\text{FIR}}$) in this type of galaxies directly.

We observed the difference of the correlation in FIR-infrared luminosity and CO luminosity with other parameters in our sample, that is, the mean value of $L_{\text{FIR}}$ ($L_{\text{FIR}} \sim 10^{11}$ L$_{\odot}$) is larger than that in $L_{\text{CO}}$ ($L_{\text{CO}} \approx 10^9$ L$_{\odot}$). This work also revealed that the actual meaning of the gas is indicated by the total mass of cold gas and CO to FIR emission spectra that are related with the molecular hydrogen material $M_{\text{H}_2}$, while increasing Far-infrared luminosity leads all these parameters to increase. The ratio $F_{100}/F_{60}$ is an indicator of the cold dust temperature $T_d$. The value of dust temperature was in the range of 26.37-55.76 K. Depending on the power-law emission ($B_\lambda \propto \lambda^n$), it was found that the increase in cold dust temperature is associated with increasing the star formation activity.

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