An Alternative View of Flat Rotation Curves.
II. The Observations

D.S.L. Soares
Observatório Astronômico da Piedade
Departamento de Física, ICEx, UFMG — C.P. 702
30161-970, Belo Horizonte — Brazil
e-mail: dsoares@fisica.ufmg.br

Jan. 1994

Abstract

The rotation curves of 20 spiral galaxies are examined in the light of a toy model (Soares 1992) which has as the main feature the assignment of a high M/L ratio (= 30; \( H_0 = 50 \text{ km s}^{-1}\text{Mpc}^{-1} \)) to the visible matter. The observed rotation of all galaxies can be accommodated without the assumption of a dark halo.

Moreover, the suggestion is made that the fact that almost all available rotational velocity measurements are derived from emission lines emitted by galaxian gas (either neutral or ionized) makes them inappropriate as tracers of the galaxy gravitational potential. To account for that, the model introduces an effective potential meant to describe the hydrodynamics inside a gaseous disk. The general morphology of the curves (i.e., the presence of a plateau in \( V(r) \times r \)) is interpreted in this framework as a consequence of the hydrodynamical characteristics of galaxian disks.

The Tully-Fisher relation is expressed in terms of model parameters and used as an additional constraint in the process of fitting the model to the observed rotation of the galaxies.
Resumen

Son investigadas las curvas de rotación de 20 galaxias espirales usando el modelo propuesto por Soares (1992) que tiene como característica principal a de atribuir una alta razón M/L (= 30; $H_0 = 50 \text{ km s}^{-1}\text{Mpc}^{-1}$) para la materia visible. La rotación observada de todas las galaxias pueden ser acomodadas sin hacer la suposición de un halo obscuro.

Sin embargo, se sugiere que el hecho de que casi todas las medidas disponibles de velocidades de rotación son deducidas a partir de líneas emitidas por el gas de las galaxias (neutro o ionizado) las hace inadecuadas como indicadoras del potencial gravitacional. Para considerar esto, el modelo introduce un potencial efectivo apropiado para describir la hidrodinámica dentro del disco gaseoso. La morfología general de las curvas (i.e., la presencia de un plateau en $V(r) \times r$) es interpretada, neste tratamiento, como una consecuencia de las características hidrodinámicas de los discos galácticos.

La relación de Tully-Fisher se expresa en términos de los parámetros del modelo y es usada como una restricción adicional en el proceso de ajuste del modelo a la rotación observada de las galaxias.

Key Words: spiral galaxies – galaxian rotation – dark matter

1 Introduction

The mass discrepancy in spiral galaxies is still an unsolved problem in astrophysics. Topical or review papers have been copiously written in the last decade (e.g., Faber and Gallagher 1979; Rubin et al. 1982; Whitmore et al. 1984; van Albada et al. 1985; van Albada and Sancisi 1986; Trimble 1987; Sanders 1990; Broeils 1992; Ashman 1992; Persic and Salucci 1993; etc) demonstrating renewed interest on the subject.

The orthodox explanation of flat rotation curves of spiral galaxies is that they are the result of combined effects of luminous matter, with M/L typical of the solar neighborhood, and dark matter with much higher M/L. Luminous matter accounts for the rotation inside the luminous body and a dark extended halo is needed to fully account for the values above Keplerian observed in the outer regions of spirals. Popular alternative views include modifications of Newtonian dynamics (or gravity, e.g., Milgrom 1983, 1988.
1991), and modifications of the classical view of spiral galaxies (e.g., Valentijn 1990; González-Serrano and Valentijn 1991; Battaner et al. 1992). This paper follows another (Soares 1992, hereafter Paper I) where we put forward an alternative idea for the mass discrepancy query.

In Paper I we suggested that real M/L for the luminous body of spiral galaxies should be those obtained from binary galaxy studies (e.g., Schweizer 1987; Soares 1989; etc), which are as large as ten or fifteen times the local solar M/L. These values, in spite of disagreeing with classical stellar population calculations (e.g., Larson and Tinsley 1978), are by no means ruled out by standard stellar population synthesis of spiral galaxies; it is almost common sense nowadays that a population synthesis calculation of spiral galaxies can yield virtually any value of M/L, given the uncertainty on stellar metallicities and ages.

Furthermore, we pointed out that the observations of the rotation of spiral galaxies are inferred almost always from Doppler shifts of emission lines generated either by ionized or by neutral galaxian gas, and gas motion cannot be used as a reliable tracer of the gravitational potential. Rather, gas motion is ruled by an effective potential wherein hydrodynamical effects are incorporated.

The last two paragraphs state the two basic work hypotheses of the alternative model (hereafter AMOD) described in Paper I.

In section 2 a short summary of the toy model of Paper I is made. The rotation curves of 20 spiral galaxies, observed by Rubin et al. (1982) are investigated in the framework of the AMOD potential (see equation (1), below). In order to reduce the number of free parameters, we assume a fixed M/L for all of the galaxies in our sample. The adopted value is $M/L = 30$ (for $H_o = 50$ km s$^{-1}$Mpc$^{-1}$, here and throughout this paper). This figure is consistent with binary galaxy studies and is further justified by the application of the toy model to the well-known spiral galaxy NGC3198 (van Albada et al. 1985; Begeman 1987, 1989; etc); this is done in section 3. In section 4, an expression for the Tully-Fisher relation (Tully and Fisher 1977), in terms of model parameters, is derived, the fitting process is described and applied to the sample. The resulting Tully-Fisher diagram is plotted as well. A brief discussion of the results and our final conclusions are presented in section 5.
2 AMOD

The overall kinematics of gas in spiral galaxy disks is derived from the toy potential

\[ U(r) = \frac{GM}{r} \left( 1 + \beta e^{-r/r_o} \right) , \]

where \( \beta \) and \( r_o \) are intrinsic galaxian scale parameters.

A Seeliger-Neumann type potential (North 1965; Assis 1992) was added to the Newtonian gravitational potential in order to describe the hydrodynamics inside a spiral gaseous disk; the parameters \( \beta \) and \( r_o \) determine the range of applicability of the new potential component in each galaxy. In Paper I, this additional component is associated with a kind of buoyancy potential. It is shown there also that equation (1) can be derived from a simple phenomenological description of the dynamics of gas bubbles inside smooth gaseous disks.

The circular velocity of test particles is easily derived from the AMOD potential:

\[ v_{\text{circ}}(r) = \left\{ \frac{GM}{r} \left[ 1 + \beta \left( 1 + \frac{r}{r_o} \right) e^{-r/r_o} \right] \right\}^{1/2} . \]

The Keplerian rotation curve derived from the light profile of a spiral galaxy plus the usual values of \( M/L \) is below observed gas rotation in the outer regions. The conventional dark matter approach is to adopt an extended halo in such a way that the model velocities are pushed up to the observed levels. AMOD, on the other hand, assumes a higher \( M/L \), resulting in that the Keplerian curve will be located above the observed rotation curve. With properly chosen \( \beta \) and \( r_o \), it was shown in Paper I that equation (2) pulls down such an overestimated rotation profile to the observed levels. This is illustrated in Figure 1, where we plot the rotation curve of a conventional \( M/L = 3 \) spiral galaxy. The Keplerian circular velocities are below the observations and are reconciled with them with the aid of a dark halo. Also shown is the Keplerian rotation curve of a \( M/L = 30 \) spiral galaxy that does not fit the observations as well. In this latter case the AMOD potential is applied and the observations are now well fitted. The exponential decay component present in the AMOD potential represent an additional repulsive force of hydrodynamical origin, which acts on the gas test particles that are tracing the galaxy rotation.
3 AMOD fit to NGC3198

As we have pointed out in Paper I, AMOD has the same mathematical formulation as the model suggested by Sanders (1984, 1986) to account for mass discrepancies in spiral galaxies, i.e., both are described by the same potential given by equation (1) with the sole difference that, in Sanders’ model, the gravitational constant $G$ is replaced by a new $G_\infty$ (see below). This model, named FLAG (finite length-scale anti-gravity), was later abandoned by Sanders (e.g., 1990) mainly on the grounds of its inability to explain one of the most important observed features of spiral galaxies, namely the Tully-Fisher relation.

In FLAG, due to the new potential component (the very same Seeliger-Neumann potential shown above) the “effective” gravitational constant is now $G_\infty = G/(1 + \beta)$, where $\beta$, in the context of FLAG, is the coupling constant of the additional component of gravity \footnote{It is important to stress that in AMOD such a component is not an additional component of gravity, rather, it is a part of the “effective” galaxian potential, and is responsible for describing the hydrodynamical behavior of gas test particles inside a gaseous disk.}. $G$ is the usual Newtonian gravitational constant. Sanders has used the galaxy NGC3198 to find out what the values of FLAG’s universal constants, $r_o$ and $\beta$, are. He found, for a luminous disk with $M/L = 2.4$, $r_o = 36$ kpc and $\beta = -0.92$ (with $H_o = 50$ km s$^{-1}$Mpc$^{-1}$). These values can be used to calculate the AMOD $M/L$ of NGC3198, i.e., $2.4/(1 + \beta) = 30$. They are also used to fit the observed rotation curve of NGC3198 with equation (2). Again, as in Paper I, we represent $M$ by a Plummer sphere (an $n = 5$ polytrope). Its cumulative mass distribution is given by

$$M(r) = \frac{M_o r^3}{(r^2 + \epsilon^2)^{3/2}} ,$$

(3)

where $M_o$ is the total galaxy mass and $\epsilon$ is the Plummer sphere core radius. In order to account for the fact that spirals have constant central surface brightness of $\approx 140$ L$_\odot$pc$^{-2}$ (Freeman 1970; Schweizer 1976), the core radius is scaled to the total galaxy mass as (e.g., Sanders 1988):

$$\epsilon = 1.6 \ M_o^{1/2} .$$

(4)

$M_o$ is given in units of $10^{11}$ M$_\odot$ and $\epsilon$ in kpc. The total luminosity (B band) of NGC3198 is $2.0 \times 10^{10}$ L$_{B\odot}$ (Begeman 1987), which implies $M_o =$
6.0 \times 10^{11} \, M_\odot \text{ and } \epsilon = 3.9 \, \text{kpc}. Equation (4) is also used below (section 4) to model all the sample galaxies.

Figure 2 shows the fit to the observed rotation curve of NGC3198 obtained with the above-mentioned parameters. The only difference between the AMOD fit and FLAG’s one is the use by Sanders of an exponential disk to model the galaxy. As one sees, with the spherical symmetric Plummer model the fit does not change too much. The general behavior of the rotation curve is reproduced in spite of losing fine features.

From the above investigation on NGC3198, and from results of binary galaxy studies (Schweizer 1987; Soares 1989; etc), we shall adopt the value of $M/L = 30$ to proceed with the AMOD analysis. Of course, the $M/L$ of a given galaxy is an intrinsic parameter and might vary from galaxy to galaxy. The point here is that fixing $M/L$, we gain in reducing the free parameter space while not being too far from what ought to be individual values of $M/L$ for each galaxy. It is worthwhile noting that, in the context of AMOD, such a high $M/L$ is assigned to the visible body of the galaxy instead of being justified by the artificial assumption of the existence of an extended dark halo surrounding the visible galaxy.

The sample of 20 Sb galaxies of Rubin et al. (1982) will be considered in the next section taking into account the AMOD potential and the Tully-Fisher relation.

4 AMOD and the Tully-Fisher relation

The main question in this section is whether AMOD is consistent or not with the Tully-Fisher relation. To investigate that, a set of observed rotational profiles is modeled with AMOD having the Tully-Fisher relation as an additional fitting constraint.

To begin with, one needs a convenient expression for the Tully-Fisher relation, i.e., a relationship which involves the relevant AMOD parameters. Let us consider the following form of the Tully-Fisher relation (Aaronson, Huchra and Mould 1979):

$$L = k_{TF} \, V_p^4,$$

which, in spite of being oversimplified, is very useful to the sort of investigation underway.
For the evaluation of $k_{TF}$ we have considered the spiral galaxies observed in the 21 cm line of neutral hydrogen by Begeman (1987). We took, for Begeman’s eight galaxies, the luminosity in the B band ($L$) and the plateau velocity of the rotation curve ($V_p$). From a plot of $L \times V_p^4$, and in a system of units where luminosity is given in $10^{11} L_\odot$, time in $10^8$ s, velocity in units of 97.8 km/s and $G = 4.50$, we derive $k_{TF} = 2.87 \times 10^{-2}$. A range of 30% error is allowed in equation (5) (see below) to account for the scattering in the diagram $L \times V_p^4$ which was used for the determination of $k_{TF}$.

The AMOD parameters are introduced in equation (5) through the expression for the circular velocity given by equation (2). Let $V_p = v_{circ}(r = 2 \times R_{25})$, where $R_{25}$ is the de Vaucouleurs’ radius of the galaxy (i.e., the radius of the galaxy to the 25th B magnitude per square arcsecond isophote). This is an arbitrary value for the model plateau velocity but the particular choice of $V_p$ (at some $r \geq R_{25}$) does not change the analysis, as we have verified. The galaxy mass is converted into integrated blue luminosity via the $M/L$ ratio. We can then re-write equation (5) as

$$A = \frac{1}{Gk_{TF}V_p^2},$$

where $A$ is the AMOD index, and is given by:

$$A = \frac{M/L}{2R_{25}}\left[1 + \beta\left(1 + \frac{2R_{25}}{r_o}\right)e^{-2R_{25}/r_o}\right].$$

The Tully-Fisher relation is now expressed through a relationship between the so-called AMOD index $A$ and $V_p$ (equation (6)). $A(V_p)$ is the AMOD function one would expect if the Tully-Fisher relation can be expressed as equation (5). Equation (7) can be used then to derive an observed AMOD index ($A_{fit}$), taking into account intrinsic galaxian parameters ($\beta, r_o, R_{25}$ and $M/L$). The AMOD parameters, $\beta$ and $r_o$, are obtained from the fits to the rotation curves.

A fit of the AMOD circular velocity to Rubin et al. (1982) observations of the rotation of 20 Sb spiral galaxies was done. The fitting procedure took into account the goodness of fitting to the Tully-Fisher relation (equation (6)) too. A quantitative measure of the fitting of $A_{fit}$ (defined through equation (7)) to equation (6) can be given by $\delta A$, defined by

$$\delta A = \frac{A(V_p) - A_{fit}}{0.30A(V_p)}.$$
This quantity gives the amount of deviation of the fitted AMOD index from the predicted $A(V_p)$ curve in terms of a 30% error bar. The AMOD solutions ($V_{AMOD}(r)$) for the rotation curves measured by Rubin et al. ($V_{obs}(r)$) are those that simultaneously minimize $|\delta A|$ and $\Delta V = |V_{obs}(r) - V_{AMOD}(r)|$.

Figure 3 and Figure 4 show the result of the fitting process. The observed rotation curves by Rubin et al. are shown together with the AMOD fit in Figure 3. The Tully-Fisher relation is shown in Figure 4. Table 1 presents the relevant parameters of all studied galaxies. Column 1: galaxy name (NGC or UGC); column 2: plateau velocity, as given by Rubin et al. and by Begeman in the case of NGC3198; column 3: de Vaucouleurs’ radius, in kpc; column 4: characteristic AMOD radius, in kpc; column 5: AMOD coefficient $\beta$; column 6: AMOD index, defined by equation (7); column 8: relative error in $A$, defined by equation (8).

Both trends, in the rotational profiles and in the Tully-Fisher relation, are reasonably well reproduced, as can be seen in Figures 3 and 4. It must be pointed out that the fact that the fitting procedure consists in minimizing $|\delta A|$ and $\Delta V$ does not necessarily imply that the distributions of points in the $A \times V_p$ diagram should follow the general trend given by equation (6); the points could be distributed in any possible way in that plane but, amongst all of them, they do follow the behavior predicted from the observed Tully-Fisher relation.

5 Discussion and Conclusion

Presently, it is a very difficult task to deny the existence of extended dark material halos surrounding spiral galaxies, yet accepting them remains as an uncomfortable position for many astronomers. The main reason for that is of course the fact that there is no direct observational evidence of such objects. They must be very dark, indeed.

Here, we have investigated the possibility of avoiding the dark halo hypothesis by means of a toy model which, in turn, suffers from a serious setback: the whole idea is based upon a drastic assumption in view of current standards, namely, it requires a spiral galaxy with an exceedingly high $M/L$ (about 10 – 15 times as large as accepted values). On the other hand, and justifying such a speculation, there is no firm direct observational evidence supporting current $M/L$ values of spiral galaxies.
A common feature of almost all model rotation curves, shown in Figure 3, is the badness of fitting in the small radius range. The AMOD potential is not able to give a detailed description of the rotational properties of spiral galaxies in the inner regions. The reason for that might be the oversimplified modeling of the hydrodynamical behavior of the gas component. Nevertheless, it gives a reasonable account of the global rotation of the gaseous medium as can be seen in the fitting of all of the sample rotation curves. It must be realized also that the Plummer sphere cannot represent details of the luminosity (mass) profiles of real galaxies, which has certainly contributed for some of the features shown in Figure 3.

The main point we want to make here is that disk rotation curves (either from gas emission lines or absorption from young stars) are not reliable to trace out the gravitational potential of a spiral galaxy as a whole. The toy model, discussed here and in Paper I, suggests that gas rotation may be indicating internal properties of the gaseous disk component rather than giving global information about the galaxy mass distribution.

AMOD can be tested observationally through a comparison between stellar and gas rotation curves in the inner regions of spiral galaxies. There, the effects caused by the gaseous character of the material are stronger than in the outer regions. That could be done from absorption line measurements, in the case of stellar rotation curves, and from emission line measurements from HII regions. Of course, the gravitational potential is the same for both gas and stars but the question is whether the effective galactic potential for gas is the same as for the stellar component. The physical processes acting on the gas component are certainly different from those on the stellar component. A special care must be taken when choosing the lines for the absorption measurements: one should look preferentially to old disk stars. Young OB stars preserve the kinematical characteristics of the gas medium where they were formed and are likely to give the same results for the rotation velocities as compared to the gas measurements.

Acknowledgment — Partial support from CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil — Process No. 300193/90-4) is gratefully acknowledged. I would like to thank Dr. F.O. Véas Letelier for the help in translating the abstract to Spanish.
References
Aaronson, M., Huchra, J., Mould, J.: 1979, Astrophys. J. 229, 1
Albada, T.S. van, Bahcall, J.N., Begeman, K., Sancisi, R.: 1985, Astrophys. J. 295, 305
Albada, T.S. van, Sancisi, R.: 1986, Phil. Trans. Royal Soc. Lond. A 320, 447
Ashman, K.M.: 1992, Publ. Astron. Soc. Pacific 104, 1109
Assis, A.K.T.: 1992, Apeiron 13, 3
Battaner, E., Garrido, J.L., Membrado, M., Florido, E.: 1992, Nature 360, 624
Begeman, K.G.: 1987, Ph.D. Thesis, University of Groningen
Begeman, K.G.: 1989, Astron. Astrophys. 223, 47
Broeils, A.H.: 1992, Ph.D. Thesis, University of Groningen
Faber, S.M., Gallagher, J.S.: 1979, Ann. Rev. Astron. Astrophys. 17, 135
Freeman, K.C.: 1970, Astrophys. J. 160, 811
González-Serrano, J.I., Valentijn, E.A.: 1991, Astron. Astrophys. 242, 334
Larson, R.B., Tinsley, B.M.: 1978, Astrophys. J. 219, 46
Milgrom, M.: 1983, Astrophys. J. 270, 365
Milgrom, M.: 1988, Astrophys. J. 333, 689
Milgrom, M.: 1991, Astrophys. J. 367, 490
North, J.D.: 1965, The Measure of the Universe – A History of Modern Cosmology, Clarendon Press, Oxford
Persic, M., Salucci, P.: 1993, Mon. Not. R. astr. Soc. 261, L21
Rubin, V.C., Ford, W.K., Thonnard, N., Burstein, D.: 1982, Astrophys. J. 261, 439
Sanders, R.H.: 1984, Astron. Astrophys. 136, L21
Sanders, R.H.: 1986, Astron. Astrophys. 154, 135
Sanders, R.H.: 1988, Mon. Not. R. astr. Soc. 235, 105
Sanders, R.H.: 1990, Astron. Astrophys. Rev. 2, 1
Schweizer, F.: 1976, Astrophys. J. Suppl. Ser. 31, 313
Schweizer, L.S.: 1987, Astrophys. J. Suppl. Ser. 64, 427
Soares, D.S.L.: 1989, Ph.D. Thesis, University of Groningen
Soares, D.S.L.: 1992, Rev. Mexicana Astron. Astrof. 24, 3 (Paper I)
Trimble, V.: 1987, Ann. Rev. Astron. Astrophys. 25, 425
Tully, R.B., Fisher, J.R.: 1977, Astron. Astrophys. 54, 661
Valentijn, E.A.: 1990, Nature 346, 153
Whitmore, B.C., Rubin, V.C., Ford, W.K.: 1984, Astrophys. J. 287, 66
Table 1
Parameters and AMOD indices for sample galaxies

| Name   | $V_p$ | $R_{25}$ | $r_o$ | $-\beta$ | $\Delta$ | $\delta\Delta$ |
|--------|-------|----------|-------|----------|----------|---------------|
| N3200  | 282.  | 46.0     | 140.0 | 0.90     | 0.74     | -0.68        |
| N7606  | 246.  | 39.8     | 150.0 | 0.91     | 0.68     | -1.48        |
| N3223  | 255.  | 34.8     | 120.0 | 0.92     | 0.80     | -0.98        |
| N3145  | 275.  | 33.8     | 100.0 | 0.92     | 0.96     | -0.07        |
| U12810 | 235.  | 51.4     | 110.0 | 0.95     | 0.81     | -1.31        |
| N7083  | 222.  | 39.0     | 120.0 | 0.92     | 0.80     | -1.56        |
| N1085  | 310.  | 34.8     | 260.0 | 0.84     | 0.80     | +0.12        |
| N2815  | 280.  | 26.5     | 180.0 | 0.82     | 1.2      | +0.85        |
| N2590  | 256.  | 39.6     | 100.0 | 0.88     | 1.1      | -0.14        |
| N3054  | 239.  | 25.7     | 60.0  | 0.90     | 1.7      | +1.03        |
| N1620  | 252.  | 29.8     | 55.0  | 0.92     | 1.8      | +1.72        |
| N7217  | 254.  | 15.1     | 160.0 | 0.78     | 2.3      | +3.37        |
| N7537  | 144.  | 18.3     | 90.0  | 0.94     | 0.98     | -2.42        |
| N1325  | 184.  | 18.8     | 36.0  | 0.93     | 2.6      | +0.69        |
| N1353  | 226.  | 14.0     | 140.0 | 0.84     | 1.9      | +0.97        |
| N1515  | 153.  | 13.6     | 100.0 | 0.86     | 1.8      | -1.40        |
| N4448  | 190.  | 11.0     | 120.0 | 0.84     | 2.4      | +0.49        |
| N3067  | 161.  | 9.6      | 80.0  | 0.90     | 1.9      | -1.11        |
| N2708  | 241.  | 14.7     | 120.0 | 0.86     | 1.7      | +0.99        |
| N4800  | 179.  | 4.9      | 48.0  | 0.84     | 5.4      | +4.41        |
| N3198  | 149.  | 17.1     | 36.0  | 0.92     | 2.7      | -0.65        |

Notes: N3198 observed in HI by Begeman (1987), and the other galaxies in optical emission lines by Rubin et al. (1982). $H_o = 50$ km s$^{-1}$Mpc$^{-1}$, and $M/L = 30$ for all galaxies. The plateau velocity, $V_p$, is given in km/s, and $R_{25}$ and $r_o$ in kpc.
Captions to the Figures

Figure 1: A typical flat rotation curve can be explained by assuming galaxy luminous matter with solar neighborhood M/L plus a dark halo. Alternatively, it can also be explained with luminous matter having a high M/L and test particle circular velocities given by AMOD.

Figure 2: The filled squares are the observed HI circular velocities for NGC3198 (Begeman 1987). The solid line is the AMOD fit to the observations with $\beta = -0.92$, $r_o = 36$ kpc, and $M/L = 30$. The galaxy mass distribution is modeled with a Plummer model (see text).

Figure 3: The squares represent the observations by Rubin et al. (1982), and the line is the AMOD fit to the rotation curve. The relative error in the AMOD index ($\delta_A$) is given in each frame.

Figure 4: The solid line is given by equation (6), i.e., the Tully-Fisher relation in terms of the AMOD parameters. The dashed lines show the 30\% error bar strip. The points were obtained from the fits to the rotation curves shown in Figure 3, and follow the general trend given by the predicted curve.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9402026v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9402026v1
This figure "fig1-3.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9402026v1
This figure "fig1-4.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9402026v1