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THE EXTRAGALACTIC GAMMA-RAY BACKGROUND

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Abstract. The *COMPTEL* and *EGRET* detectors aboard the Compton Gamma-Ray Observatory measured an extragalactic γ-ray background (EGRB) extending from ~ 1 MeV to ~ 100 GeV. Calculations performed making reasonable assumptions indicate that blazars can account for the background between ~ 10 MeV and ~ 10 GeV. Below 30 MeV, the background flux and spectrum are not very well determined and a dedicated satellite detector will be required to remedy this situation. Below 10 MeV, supernovae and possibly AGN may contribute to the extragalactic background flux. Above 10 GeV, the role of blazars in contributing to the background is unclear because we do not have data on their spectra at these energies and because theoretical models predict that many of them will have spectra which should cut off in this energy range. At these higher energies, a new component, perhaps from topological defects, may contribute to the background, as well as X-ray selected BL Lac objects. *GLAST* should provide important data on the emission of extragalactic sources above 10 GeV and help resolve this issue. *GLAST* may also be able to detect the signature of intergalactic absorption by pair production interactions of background γ-rays of energy above ~ 20 GeV with starlight photons, this signature being a steepening of the background spectrum.

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1. INTRODUCTION

The EGRB measured by *EGRET* can be represented as of the power-law form

$$\frac{dN_\gamma}{dE} = (7.32 \pm 0.34) \times 10^{-8} \left(\frac{E}{0.451\mathrm{GeV}}\right)^{-2.10\pm0.03} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1} \quad (1)$$

between 0.1 and ~ 50 GeV (statistics limited) [1]. At energies below 30 MeV, the EGRB spectrum appears to be steeper, as determined from an analysis of *COMPTEL* data [2].

Figure 1, taken from Ref. [3], shows a comparison between the diffuse inner-galactic and extragalactic spectra measured by *EGRET*. It shows that these diffuse spectra have fundamentally different origins. The galactic spectrum shows evidence of the

predicted "bump" from neutral pion decay [4], [5] whereas the extragalactic spectrum shows no such feature as would be expected from cosmic ray p - p interactions. This type of direct spectral information eliminates purely diffuse extragalactic cosmic-ray interaction origin models, such as have been proposed [6] as explanations for the EGRB.

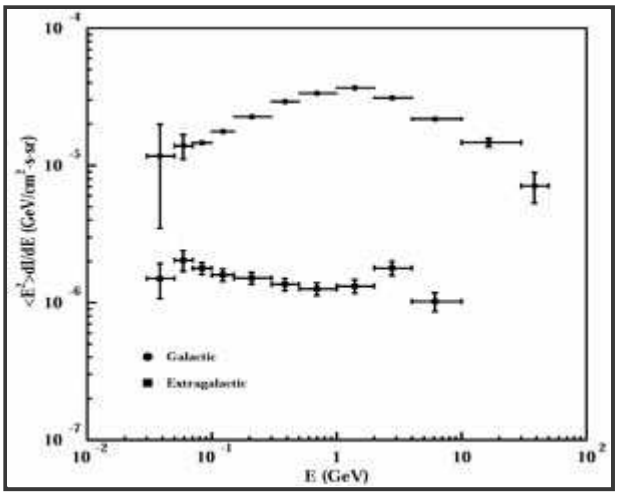

Figure 1. Comparison of Galactic and extragalactic diffuse spectra as determined by *EGRET*.

2. THE EGRB FROM 0.03 TO 10 GEV

The most promising model proposed for the origin of the GeV range extragalactic γ-ray background (EGRB), first detected by *SAS-2* and later confirmed by *EGRET* [1], is that it is the collective emission of an isotropic distribution of faint, unresolved blazars (See Ref. [7] and references therein.). Such unresolved blazars are a natural candidate for explaining the EGRB since, they are the only significant non-burst sources of high energy extragalactic γ-rays detected by *EGRET*.

2.1. The Unresolved Blazar Model:

To determine the collective output of all γ-ray blazars, one can use the observed *EGRET* distribution of γ-ray luminosities and extrapolate to obtain a "direct" γ-ray luminosity function (LF) per comoving volume, $f_\gamma(l_\gamma, z)$ [8]. Alternatively, one can make use of much larger catalogs at other wavelengths and assume a relationship between the source luminosities at the catalog wavelength and the GeV region [9], [10]. Both methods have uncertainties.

With regard to the former method, only the "tip of the iceberg" of the γ-ray LF has been observed by *EGRET*. Lower luminosity γ-ray sources whose fluxes at Earth would fall below *EGRET*'s minimum detectable flux, *i.e. EGRET*'s point source sensitivity (PSS), are not detected. Extrapolating the γ-ray LF to fainter source luminosities must then involve some extra assumption or assumptions.

We have chosen to use the latter method and have assumed a linear relation between the luminosities of a source at radio and γ-ray wavelengths in an attempt to estimate a LF which would hold at fainter luminosities. The extent of such a correlation is by no means well established [10] - [12]. However, since most theoretical models invoke the same high energy electrons as the source of both the radio and γ-ray emission, a quasi-linear relation between radio and γ-ray luminosities is a logical assumption. In fact, recent observations support this supposition [13].

We used this latter method to estimate the contribution of unresolved blazars to the EGRB, and found that up to 100% of the EGRB measured by can be accounted for [7]. Our model assumes a linear relationship between the differential γ-ray luminosity l_γ at E_f = 0.1 GeV and the differential radio luminosity l_r at 2.7 GHz for all sources, $l_\gamma \equiv \kappa\, l_r$ with κ determined by th observational data. One can then used the measured radio LF $f_r(l_r, z)$ for blazars (flat spectrum radio sources) [14] to calculate the collective γ-ray output of all blazars. This LF is shown in Figure 2.

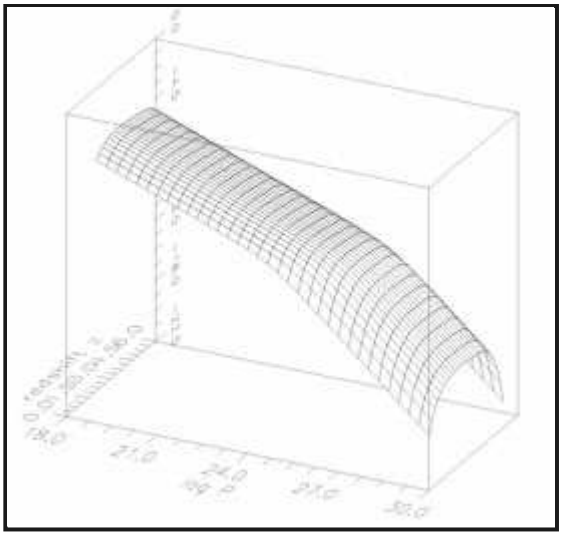

Figure 2. Radio luminosity (power) function at 2.7 GHz after Dunlop and Peacock [14].

The simplified elements of our calculations are as follows: We assume that blazars spend 97% of their time in a quiescent state and the remaining 3% of their time in a flaring state We assume that the γ-ray and radio LFs in their quiescent state are related by $f_\gamma(l_\gamma, z) = \kappa^{-1} f_r(\kappa^{-1}{}_\gamma, z)$. This relation changes by an average γ-ray "amplification factor", $< A > = 5$, when the blazars are flaring. We assume that γ-ray spectra for all sources are of the power-law form $l(E) = l_\gamma (E / E_f)^{-\alpha}$, where α is assumed to be independent of redshift. We have taken the distribution of such spectral indeces, α, from appropriately related *EGRET* data. We also assume a slight hardening of the blazar spectra when they are in the flaring state which is supported by the *EGRET* data. For further details, see Ref. [7].

The number of sources N detected is a function of the detector's PSS at the fiducial energy E_f, $[F(E_f)]_{min}$, where the integral γ-ray photon flux F is related to l_γ by

$$F(E) = l_\gamma (E/E_f)^{-\alpha} / 4\pi\alpha(1+\alpha)^{\alpha+1} R_0^2 r^2, \quad (2)$$

where $R_0\, r(1 + z)$ is the luminosity distance to the source. The number of sources at redshift z seen at Earth with an integral flux $F(E_f)$ is given by

$$\frac{d\mathcal{N}}{dF(E_f)} \Delta F(E_f) = \int 4\pi R_0^3 r^2\, dr\, f_\gamma(l_\gamma, z(r)) \Delta l_\gamma, \quad (3)$$

where l_γ in the integrand depends on $z(r)$ and $F(E_f)$ from eq. 2. The LF, f_γ, includes both quiescent and flaring terms. Figure 3 shows the results of our calculation of the number of sources versus flux above 0.1 GeV, *i.e.*, our predicted source count curve, compared to the *EGRET* detections [7]. The cutoff at ~ 10^{-7} cm^{-2} s^{-1} for E_f = 0.1 GeV, their quoted PSS, is evident by the dropoff in the detected source count below this flux level.

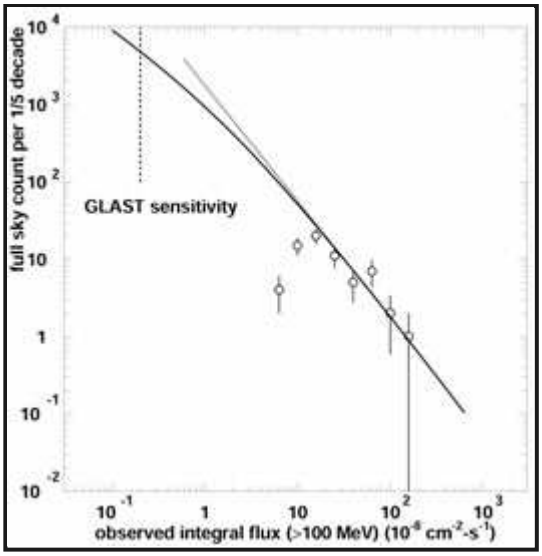

Figure 3. Source number count per one-fifth decade of integral flux at Earth The straight dotted line is the Euclidean relation $N(>F) \propto F^{-3/2}$ for homogeneous distribution of sources . The open circles represent the *EGRET* blazar detections and the solid line is the model prediction.

To calculate the EGRB, we integrate over all sources *not* detectable by the telescope to obtain the differential number flux of EGRB photons at an *observed* energy E_0:

$$\frac{dN_\gamma}{dE}(E_0) = \int 4\pi R_0^3 r^2\, dr \int d\alpha\, p(\alpha) \int_{l_{min}}^{l_{max}} \frac{dF}{dE}(E_0(1+z)) f_\gamma(l_\gamma, z) e^{-\tau(E_0,z)}\, dl_\gamma. \quad (4)$$

This expression includes an integration over the probability distribution of spectral indices α based on the second *EGRET* Catalog [15].

There is also an important attenuation factor in this expression; the attenuation occurring as the γ-rays produced by blazars propagate through intergalactic space and interact with cosmic UV, optical, and IR background photons to produce $e^{\pm}$ pairs. If a substantial fraction of the EGRB is from high-z sources, a steepening in the spectrum should be seen at energies above ~ 20 GeV caused by the attenuation effect [16]. Figure 4, from Ref. [16], shows the calculated EGRB spectrum (based on the *EGRET* PSS) compared to *EGRET* data. The slight curvature in the spectrum below 10 GeV is caused by the distribution of unresolved blazar spectral indeces; the harder sources dominate the higher energy EGRB and the softer sources dominate the lower energy EGRB. The steepened spectra above ~ 20 GeV in Figure 4 show the attenuation effect and its uncertainty.

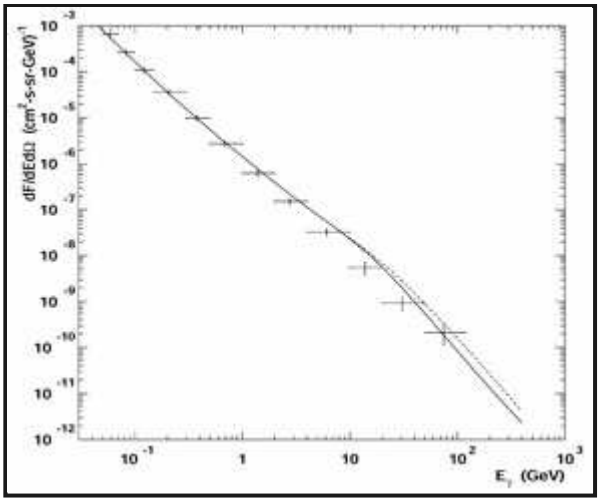

Figure 4. The predicted *EGRET* EGRB from unresolved blazars compared with the *EGRET* data. *GLAST* should see an EGRB about a factor of 2 lower at energies above 1 GeV (see text).

2.2. Critique of the Assumption of Independence of Blazar Gamma-Ray and Radio Luminosities

Chiang and Mukherjee [17] have attempted to calculate the EGRB from unresolved blazars assuming complete independence between blazar γ-ray and radio luminosities. They then used the intersection between the sets of flat spectrum radio sources (FSRSs) of fluxes above 1 Jy found in the Kühr catalogue and the blazars observed by *EGRET* as their sample, optimizing to the redshift distribution of that intersection set to obtain a LF and source redshift evolution. Using this procedure, they derived a LF which had a low-end cutoff at 10^{46} erg s^{-1}. Then, with no fainter sources included in their analysis, they concluded that only ~ 1/4 of the 0.1 to 10 GeV EGRB could be accounted for as unresolved blazars and that another origin must be found for the EGRB in this energy range.

We have argued above that it is reasonable to expect that the radio and γ-ray luminosities of blazars are correlated. Any such correlation will destroy the assumption of statisitical independence made by Chiang and Mukherjee and introduce a bias in their analysis. In fact, their analysis leads to many inconsistencies. Among them are the following:

A. The LF derived by Chiang and Mukherjee [17] allows for no sources with luminosities below 10^{46} erg s^{-1}. In fact, *all* of the six sources found by *EGRET* at redshifts below ~ 0.2 have luminosites between ~ 10^{45} erg s^{-1} and ~ 10^{46} erg s^{-1} [18]. Elimination of fainter sources from the analysis can only lead to a lower limit on the EGRB from unresolved blazars. The fainter sources contribute significantly in acounting for unresolved blazars being the dominant component of the EGRB. (In this regard, see also, Ref. [19])

B. Chiang and Mukherjee limit the *EGRET* sources in their analysis only to the FSRSs in the Kühr catalogue. However, if there is truly no correlation between blazar radio and γ-ray luminosities, then any of the millions of FSRSs given by the Dunlop and Peacock radio LF [14] are equally likely to be *EGRET* sources. In that case, of the 50 odd sources in the 2nd *EGRET* catalogue, virtually *none*, *i.e.* ~ 10^{-6}, should be Kühr sources.

The above discussion indicates that the assumption of non-correlation between the radio and γ-ray fluxes of blazars made by Chiang and Mukherjee in their analysis is not a good one and that this assumption invalidates their conclusions.

2.3. *GLAST* and the EGRB:

With an estimated point source sensitivity (PSS) nearly two orders of magnitude lower than *EGRET*'s, *GLAST* will be able to detect $O(10^2)$ times more blazars than *EGRET*, and measure the EGRB spectrum to > 1 TeV (assuming the *EGRET* power law spectrum). These two capabilities will enable *GLAST* to either strongly support or reject the unresolved-blazar hypothesis for the origin of the EGRB.

Figure 3 shows that $O(10^3)$ blazars should be detectable by *GLAST*, assuming it achieves a PSS of ~ 2×10^{-9} cm^{-2} s^{-1}. Using this PSS and our derived source count curve as shown in Figure 3, we have estimated that the remaining "diffuse" EGRB seen by *GLAST* should be a factor of ~ 2 lower for E > 1 GeV. Below 1 GeV, this factor of 2 will not apply because source confusion

owing to the poorer angular resolution of *GLAST* at these lower energies will reduce the number of blazars resolved out of the background.

We conclude that *GLAST* can test the unresolved blazar background model in three ways:

A. *GLAST* should see roughly 2 orders of magnitude more blazars than *EGRET* because of its ability to detect the fainter blazars which contribute to the EGRB in our model. It can thus make a much deeper determination of the source count curve. *GLAST* can also determine the redshift distribution of many more identified γ-ray blazars, using its better point source angular resolution to make identifications with optical sources having measured redshifts. With its larger dynamic range, *GLAST* can then test the assumption of an average linear relation between the γ-ray and radio fluxes of identified blazars. All of these determinations will test the basic assumptions and results of our model.

B. With its better PSS, *GLAST* will resolve out more blazars from the background. Thus, fewer unresolved blazars will be left to contribute to the EGRB. reducing the level of the measured EGRB compared to *EGRET*'s by a factor of ~ 2 if our predictions are correct.

C. The much greater aperture of *GLAST* at 100 GeV will allow a determination of whether or not a steepening exists in the EGRB, since the number of EGRB γ-rays recorded by *GLAST* above 100 GeV will be of order 10^3 to 10^4, assuming a continuation of the *EGRET* power-law spectrum. Such a steepening can be caused by both absorption and intrinsic turnovers in blazar spectra. Given enough sub-TeV spectra of individual blazars with known redshifts, these two effects can be separated.

3. THE EGRB BETWEEN 0.5 AND 30 MEV

The explanation for the origin of the EGRB at energies in the range of several MeV must be a non-blazar explanation. The reason for this is that while the EGRB spectrum in this energy range appears to be *softer* than that at higher energies [2], the data from *OSSE* and *COMPTEL* on individual blazars in this energy range indicate a *harder* spectrum than that at higher energies. The measured blazar spectra appear to break below ~ 10 MeV to spectra with a typical power-law index of ~ 1.7 [20]. Thus, even if unresolved blazars account for almost all of the EGRB in the 0.1 to 10 GeV range, this cannot be the case at lower energies.

Calculations have shown that a superposition of redshifted lines from Type Ia and Type II supernovae should reasonably provide a significant component of the EGRB at energies ~ 1 MeV. The important line emission is from the decay chain ^{56}Ni -> ^{56}Co -> ^{56}Fe and also from the decay of ^{26}Al, ^{44}Ti and ^{60}Co [21], [22]. However, supernovae cannot account for the entire EGRB in this energy range, since they produce no line emission above 3.5 MeV.

Another serious possibility as a significant contributer to the multi-MeV EGRB is non-thermal tails in the energy spectra of the AGN [23]. These would be the same AGN which have recently been resolved out by the *Chandra* telescope and found to be the dominant component of the once unresolved X-ray background [24].

A recent discussion of AGN models fitting the X-ray background has been given in Ref. [25]. While there are no data on individual AGN in the multi-MeV energy range at the present time, Stecker, Salamon and Done [23] have pointed to the galactic black hole candidate Cyg. X-1 as an example of a black hole source which has been shown from *COMPTEL* data to have a non-thermal tail extending to multi-MeV energies [26]. If the extragalactic black hole sources which make up the X-ray background have such non-thermal tails, they may account for most of the EGRB in the multi-MeV range.

It should be noted that the extraction of the ~ MeV EGRB from the raw *COMPTEL* data is a difficult process, in part owing to the fact that this double Compton scattering telescope was not designed to measure this background. In our opinion, a dedicated low-mass, free flyer satellite, specifically designed to measure the EGRB at low γ-ray energies will be required in order to accurately determine its characteristics.

4. THE EGRB ABOVE 10 GEV

It has already been pointed out that the EGRB should break above ~ 20 GeV energy owing to absorption of high energy γ-rays by pair-production interactions with lower energy starlight photons [16]. There is also another potential cause for a steepening in the EGRB from blazars. The *EGRET* detector obtained rough power-law spectral indeces for blazars in the 0.1 to 10 GeV energy decade, however, we presently have no data for these objects in the 10 to 100 GeV decade. Presently popular theoretical models predict that the spectra of highly luminous blazars will exhibit a cutoff at energies in the 10 to 100 GeV range, whereas the less luminous X-ray selected BL Lac objects can have spectra extending into the TeV energy range [27], [28].

Indeed, there have now been ground based detections of at least 5 X-ray selected BL Lac objects (Weekes, these proceedings),

some of whose spectra extend to multi-TeV energies. While no other types of blazars have been seen at TeV energies, this may be an result of intergalactic γ-ray absorption [16], [29], [30] so that we do not really know if their intrinsic spectra turn down at energies in the 10 to 100 GeV decade. The *GLAST* telescope should provide this knowledge in the not-too-distant future.

If the spectra of most blazars possess intrinsic cutoffs above 10 GeV, then the EGRB from unresolved blazars would be expected to turn over as well. This effect should be more dramatic than the steepening in the EGRB predicted from the effect of intergalactic absorption [16]. In that case, if the *EGRET* results on the EGRB up to 100 GeV are correct, a new component may be present in this higher energy range. Such a component has been predicted to be produced by the decay of ~ TeV mass higgs bosons from cosmic string processes in flat-potential supersymmetric models [31]. Of course, there may be other unknown possibilities as well.

5. CONCLUSIONS

We have a workable and testable hypothesis for the origin of the extragalactic γ-ray background measured by *EGRET*, *viz.*, that it is made up primarily of unresolved blazars. The *GLAST* γ-ray telescope, to be flown in the near future, will be able to test this hypothesis in three ways, *i.e.*, (a) by potentially resolving out and detecting thousands of more sources, (b) by measuring the remaining background flux, and (c) by determining the shape of the EGRB up to TeV energies. The many new ground-based detectors now under construction will supplement this information by discovering new extragalactic sources of γ-rays of energies above 50 GeV.

On the other hand, the mystery of the origin of the EGRB in the MeV energy range must await a better determination of this background by a future dedicated satellite detector.

REFERENCES

1. Sreekumar, P. *et al.*, Ap.J. 494, 523 (1998).
2. Kappadath, S.C. *et al.* Astron. and Astrophys. Suppl. 120, 691 (1996).
3. Stecker, F.W. and Salamon, M.H., Phys. Rev. Letters 76, 3878 (1996).
4. Stecker, F.W., ApJ 212, 60 (1977).
5. Hunter, S.D. *et al.* ApJ 481, 205 (1997).
6. Dar, A. and Shaviv, N.J., Phys. Rev. Letters 75, 3052 (1995).
7. Stecker, F.W. and Salamon, M.H., ApJ 464, 600 (1996).
8. Chiang, J. *et al.*, ApJ 452, 156 (1995).
9. Stecker, F.W., Salamon, M.H., and Malkan, M.A., ApJ 410, L71 (1993).
10. Padovani, P. *et al.*, MNRAS 260, L21 (1993).
11. Mücke, A., *et al.*, Astron. and Astrophys. Suppl. 120, 541 (1996).
12. Mattox, J.R., *et al.*, ApJ 481, 95 (1997).
13. Jorstad, S.G. *et al.*, ApJ Suppl., in press, e-print astro-ph/0101570 (2001).
14. Dunlop, J.S. and Peacock, J.A., MNRAS 247, 19 (1990).
15. Thompson, D.J. *et al.*, ApJ Suppl. 101, 259 (1995).
16. Salamon, M.H. and Stecker, F.W., ApJ 493, 547 (1998).
17. Chiang, J. and Mukherjee, R., ApJ 493, 547 (1998).
18. Chiang, J. and Mukherjee, R., target="ads_dw">ApJ 496, 752 (1998).
19. Mukherjee, R., in Proc. Intl. Symp. on High Energy Gamma-Ray Astronomy, Heidelberg, in press, e-print astro-ph/0101301.
20. Mücke, A. and Pohl, M., MNRAS 312, 177 (2000).
21. McNaron-Brown, K. *et al.*, ApJ 451, 575 (1995).
22. The, L.S., Leising, M.D. and Clayton, D.D., ApJ 403, 32 (1993).
23. Watanabe, K., *et al.*, ApJ 516, 285 (1999).
24. Stecker, F.W., Salamon, M.H. and Done, C., e-print astro-ph/9912106.
25. Mushotzky, R.F. *et al.*, Nature 404, 459 (2000).
26. Gilli, R., Salvati, M. and Hasinger, G., e-print astro-ph/0011134.
27. McConnell, M.L. *et al.*, ApJ 543, 928 (2000).
28. Stecker, F.W., De Jager, O.C. and Salamon, M.H., ApJ Letters 473, L75 (1996).
29. Fossati, G., *et al.*, MNRAS 299, 433 (1998).
30. Stecker, F.W., De Jager, O.C. and Salamon, M.H., ApJ Letters 390, L49 (1992).
31. Stecker, F.W. and De Jager, O.C., Astron. and Astrophys. 334, L85 (1998).
32. Bhattacharjee, P., Shafi, Q. and Stecker, F.W., Phys. Rev. Letters 80, 3698 (1998).